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VALUE CREATION BY AUTOMATION IN BIOGAS UPGRADING

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ABSTRACT

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Biogas upgrading is the process of removing carbon dioxide from biogas to achieve a quality equivalent to natural gas. In the upgrading process, automation has great importance for the operation and control of the process. The goal of automation is to improve quality, reliability and energy efficiency. In addition, automation has the potential to create value for customers. The goal of this Master of Science thesis is to study value creation by automation in biogas upgrading, various upgrading technologies available and the companies offering upgrading technology. To create an overview and reference base, the background theory of biogas, the most common biogas upgrading technologies and the utilization of carbon dioxide and automation were also covered. Along with an overview of the literature, the research was based on expert interviews and analyzing problems and the availability of three biogas upgrading plants. The plants examined in this thesis used water scrubbing technology.

The biogas sector has experienced problems with an inadequate automation system. Many companies in the industry have had challenges with black-box automation, reports and measuring instruments. Most biogas plants are small in capacity, which means investment costs of the plants must be kept to a minimum. This has caused deficiencies in or poor implementation of important features of the automation system in several plants.

Thirteen experts working in the biogas sector were interviewed for this thesis. The interviews and data analysis revealed what kind of problems biogas upgrading plants have had and how they can be solved. The study found that black-box automation, reports, trends and measuring devices are areas needing improvement. Black-box automation solutions – secure automation that cannot be changed without authorization – have caused problems at the plants. Data analysis supported the results of the interviews. Reports and trends have been poorly implemented in several plants, causing extra work. Opinions differed in the interviews about the use of measuring instruments, as they increase plant investment costs. However, reliable and accurate measuring devices can create value for customers and help reduce process disruptions. Improving the operation and reliability of biogas upgrading plants and determining the causes of disturbances is the overall goal in creating value for customers.

Based on the literature, interviews and a comparison of upgrading technologies, the most suitable upgrading technology for Valmet's strategy was determined. The criteria for the technology were high quality, low methane loss and the possibility of utilizing carbon dioxide without further treatment of the off-gases. The use of technology in other applications was also considered. According to the research, the most suitable technologies are amine washing and membrane separation technologies.

Keywords: Biogas, Biomethane, Biogas upgrading, Value creation, Automation

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TIIVISTELMÄ

Jussi Norja: Arvonluonti automaatiolla biokaasun jalostuksessa
Diplomityö
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Biokaasun jalostus on prosessi, jossa biokaasusta poistetaan hiilidioksidi, jotta saavutetaan maakaasua vastaava laatu. Jalostusprosessissa käytetään automaatiota prosessin hallintaan ja automaatiolla on suuri merkitys prosessin toimimiseen. Automaation tavoitteena on parantaa laatua, luotettavuutta ja energiatehokkuutta. Edellä mainittujen asioiden lisäksi automaatiolla on mahdollista luoda arvoa asiakkaalle.

Tässä työssä tutkittiin arvonluontia automaatiolla biokaasun jalostuksessa, eri jalostusteknologioita sekä jalostusteknologiaa tarjoavia yrityksiä. Työn aluksi tutkittiin taustateoriaa biokaasusta, yleisimpiä biokaasun jalostusteknologioita, hiilidioksidin hyötykäyttöä sekä automaatiota yleiskäsityksen ja vertailupohjan luomiseksi. Tutkimuksen pohjana käytettiin kirjallisuuden lisäksi asiantuntijahaastatteluita, sekä analysoitiin kolmen biokaasun jalostuslaitoksen ongelmia ja käytettävyyttä. Tutkittavissa laitoksissa on käytössä vesipesuteknologia.

Biokaasusektorilla on ilmennyt ongelmia automaatiojärjestelmän puutteiden kanssa. Monilla alalla toimivilla yrityksillä on ollut haasteita raporttien, black box -automaation ja mittalaitteiden kanssa. Suurin osa biokaasulaitoksista on kapasiteetiltaan pieniä, minkä seurauksena laitosten investointikustannukset pyritään pitämään mahdollisimman alhaisina. Investointikustannusten minimointi on aiheuttanut useilla laitoksilla puutteita automaatiojärjestelmän tärkeissä ominaisuuksissa, tai ominaisuudet ovat huonosti toteutettu.

Haastatteluilla ja laitosten ongelmia tutkimalla selvitettiin, minkälaisia ongelmia biokaasun jalostuslaitoksilla on ollut, ja miten ongelmia voisi ratkaista. Työssä haastateltiin 13 asiantuntijaa, jotka työskentelevät biokaasusektorilla. Datan analysoinnissa selvitettiin yleisimpiä syitä laitosten suunnittelemattomalle alasajolle. Tutkimuksessa selvisi, että black box -automaatio, raportit, trendit ja mittalaitteet ovat asioita, joihin toivottiin parannusta. Black box -automaatio tarkoittaa suojattua automaatiota, jota ei pysty muuttamaan ilman valtuuksia. Black box -automaatioratkaisut ovat aiheuttaneet ongelmia laitoksilla ja data-analyysi tuki haastattelujen tuloksia. Raportit ja trendit ovat huonosti toteutettu useilla laitoksilla, tämä puolestaan aiheutti ylimääräistä työtä. Haastateltavien mielipiteet mittalaitteista olivat eriäviä, sillä niiden hankinta nostaisivat laitosten investointikustannuksia. Luotettavat ja tarkat mittalaitteet loisivat kuitenkin arvoa asiakkaalle, ja niiden avulla voitaisiin vähentää häiriöitä prosessissa. Arvon luomisella pyritään parantamaan biokaasun jalostuslaitosten toimintaa, luotettavuutta sekä auttamaan häiriöiden syiden selvittämistä.

Selvitettiin Valmetin strategiaan soveltuvimman jalostusteknologian vertailemalla jalostusteknologioita kirjallisuuden ja haastatteluiden perusteella, . Kriteereinä teknologialle oli korkea laatu, vähäinen metaanihävikki sekä hiilidioksidin hyötykäytön mahdollisuus ilman poistokaasujen jatkokäsittelyä. Teknologian käyttö muissa käyttökohteissa otettiin myös huomioon. Valmetin strategiaan soveltuvimmat teknologiat tutkimuksen mukaan ovat amiinipesu- ja kalvojalostusteknologiat.

Avainsanat: Biokaasu, Biometaani, Biokaasun jalostus, Arvonluonti, Automaatio

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PREFACE

This Master of Science Thesis was prepared for Valmet Automation. I would like to thank Anna Sydänmaa and Jani Hautaluoma, who gave me the research topic and directed the research. I would also thank Jukka Konttinen and Yrjö Majanne, who supervised the thesis on behalf of Tampere University and gave me support during the thesis.

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Tampere, 2nd September 2020

Jussi Norja

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LIST OF SYMBOLS AND ABBREVIATIONS

CH_4	methane
CO_2	carbon dioxide
H_2O	water
H_2S	hydrogen sulfide
AD	anaerobic digestion
atm	standard atmosphere
CBG	compressed biogas
CC	capital cost
CCU	carbon capture and utilization
CHP	combined heat and power
DCS	distributed control system
ESA	electrical swing adsorption
LBG	liquefied biogas
LHV	lower heating value
OMC	operating and maintenance cost
OPS	organic physical scrubbing
PLC	programmable logic controller
PSA	pressure swing adsorption
SCADA	supervisory control and data acquisition
STP	standard temperature and pressure
TSA	temperature swing adsorption

1 INTRODUCTION

Biomethane is a valuable option to reduce fossil fuel consumption in the transport and energy sector. Biomethane is a renewable energy source that can be used to replace natural gas (IEAa 2020). The biomethane industry is relatively new, and the market sector is in transformation. Automation in biogas upgrading has a significant role in achieving the required quality of biomethane and in reducing CH_4 slip (Sahu et al. 2017). The following topics are examined in this thesis: the most common biogas upgrading technologies, automation used in biogas upgrading and how automation can create value for customers.

Persson published the first biogas upgrading report in 2003. It gave a comprehensive view of the sector at the time (Persson, M 2019). The market sector was relatively new then, and the report introduced how biogas plants think about biogas upgrading. Since this first report, the biogas sector has evolved, and new reports and articles have been published. In 2013, Bauer, Persson et al. (2013) wrote a perspective on biogas upgrading. At the time they published their paper, the biogas upgrading sector was growing rapidly, and the number of suppliers of the technology had grown considerably. Also, upgrading technologies had been established and become more sophisticated. In 2013, there were 225 biogas upgrading plants. By 2018, the number of upgrading plants had increased to 428. During the same period in Finland, the number of biogas upgrading plants increased from two to ten, and new plants are being built all the time. (Angelidaki et al. 2018; Bauer, Hulteberg et al. 2013) Angelidaki et al. (2018) gave a comprehensive view of the current status of biogas upgrading in 2018. A review of biogas cleaning, upgrading and utilization was published by Sun et al. (2015). This paper presented a good overview of the biogas upgrading technologies and utilization opportunities, as well as real data collected from plants to introduce the characteristics of upgrading technologies. Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. (2019a) presented recent advances in biogas upgrading technologies, along with the properties and costs of general upgrading technologies.

Biogas upgrading is a relatively new market sector. It is still evolving and finding its place in the energy sector. The automation used in biogas upgrading plants is established and uses established components. (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a) Usually, biogas upgrading plants have a small capacity (< 500 Nm3/h biomethane output), which reduces their ability to invest in a highly optimized automation system. An automation system plays a big role in biogas upgrading. However, plant automation systems have to work correctly while keeping costs down. As a result, the automation systems for upgrading plants have been missing some essential features or the features have been poorly implemented. While these features may not be critical to plant operation, they would help improve operations and make failure diagnostics easier. In summary, these features create value for the customer.

Valmet is continuously developing new products to improve customer experience. The solutions that Valmet offers can create value for customers, helping them monitor plant operations and reducing unnecessary shutdowns. The goal of the thesis is to find solutions that can create value for the customer.

Research methods in the thesis include a review of literature, interviews and data analysis. Information on the operation of the biogas upgrading plants and automation was collected from interviews. The goal of the data analysis was to research the most common problems in the biogas upgrading plants examined and the overall state of the upgrading plants. The literature and interviews were used as a base to determine the best biogas upgrading technology for Valmet. Criteria for the upgrading technology were a good quality of biomethane, low CH_4 slip and the possibility of utilizing CO_2.

The research questions of the thesis were:

1. What is the most suitable upgrading technology for Valmet?
2. How to add value for customers by using automation?
3. What technologies are being used by other companies?

This thesis consists of eight chapters. The first chapter prepares the reader by examining the subject and research problems. This chapter introduces the goal of the research and the research limits.

The second, third, fourth and fifth chapters are based on a review of the literature. The second chapter discusses the background of biogas and biomethane. The third chapter introduces biogas upgrading technologies and examines off-gas treatment. The fourth chapter examines carbon capture from biogas upgrading and utilization opportunities. The fifth chapter examines the principles of automation and automation in biogas upgrading.

The sixth chapter introduces how the experimental part of the thesis was executed. The seventh chapter presents the results and discusses the research, results of the interviews, data analysis, comparison of upgrading technologies and the suppliers of biogas upgrading technologies. The eighth chapter presents the final conclusions.

2 BACKGROUND

Biogas and biomethane are subcategories of bioenergy. Bioenergy – a renewable energy source – refers to electricity and gas that is generated from biomass, which is organic matter such as wood, agriculture products and biowaste. (Bioenergia 2020) Bioenergy is a carbon-neutral energy source, which means it does not increase the CO_2 content in the atmosphere. Producing energy from bioenergy releases CO_2 emissions into the atmosphere where they is absorbed back into nature's biological cycle when new organic matter grows. This is why bioenergy is counted as a carbon-neutral energy source. Biogas and biomethane contain methane CH_4, a greenhouse gas 25% stronger than CO_2.

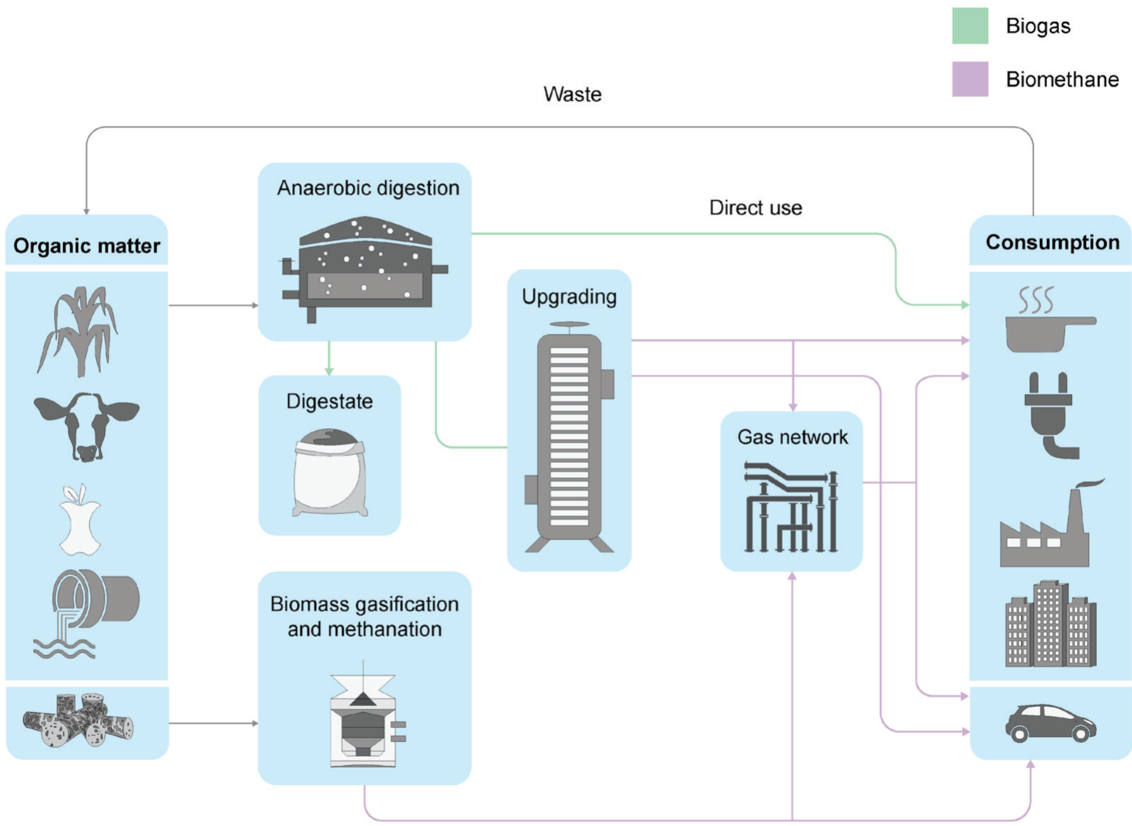

Figure 2.1. *Biogas and biomethane production pathways (IEAa 2020).*

As shown in 2.1, biogas and biomethane are produced differently and have different applications (IEAa 2020). This chapter briefly introduces their production and applications.

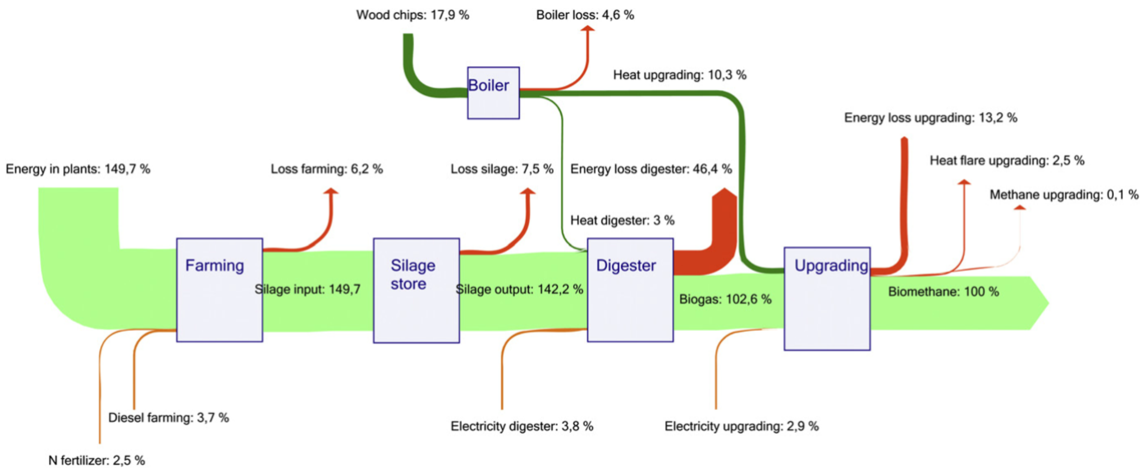

Figure 2.2. *Energy flow diagram (Adelt et al. 2011).*

Losses occur in biogas and biomethane production. Figure 2.2 shows an energy flow diagram from a biogas plant in Einbeck. The biogas is produced from anaerobic digestion and then upgraded to biomethane with amine scrubbing. The biomethane output in the plant is 500 Nm^3/h (E.ON 2011).

2.1 Biogas

Biogas is a gas mixture that contains methane (CH_4), carbon dioxide (CO_2) and other compounds such as nitrogen (N_2), water (H_2O) and hydrogen sulfide (H_2S). Biogas forms from organic material decomposing in oxygen-free conditions. The process is also known as anaerobic digestion (AD). Table 2.1 lists the compositions of biogas from AD, landfill gas and natural gas. (IEAa 2020; Motiva 2020)

Table 2.1. *Properties and composition of biogas and natural gas (Sun et al. 2015).*

Parameter	Units	Landfill gas	Biogas from AD	Natural gas
Lower heat value	MJ/Nm^3	16	23	39
CH_4	mol–%	35–65	60–70	85–92
Heavy hydrocarbons	mol–%	0	0	9
H_2	mol–%	0–3	0	-
CO_2	mol–%	15–40	30–40	0.2–1.5
H_2O	mol–%	1–5	1–5	-
N_2	mol–%	15	0.2	0.3
O_2	mol–%	1	0	-
H_2S	ppm	0–100	0–4000	1.1–5.9
NH_3	ppm	5	100	-
Total Cl	mg/Nm^3	5	100	-

Biogas can be used to replace fossil fuels in energy production. It can be burned the same way as fossil fuels in electricity and heat production. Biogas cannot be injected into natural gas networks or used in the transport sector because its CH_4 content is not as high as natural gas. However, biogas can be upgraded to biomethane. (Kymäläinen and Pakarinen 2015, pp. 17) Upgrading technologies are introduced in Chapter 3.

2.1.1 Anaerobic digestion

Anaerobic digestion is the most common biogas production method. Feedstocks are organic material such as crop residues, animal manure, organic fraction of municipal solid waste or wastewater sludge. Anaerobic digestion (AD) can be divided into four steps all occurring simultaneously: hydrolysis, fermentation, acidogenesis and methanogenesis (Mao et al. 2015). The biogas produced contains 60–70% CH_4 and 30–40% CO_2. Each step in AD requires specific microorganisms, and the process is easily disturbed if the conditions are not suitable (Kinnunen 2016, pp. 12).

In addition to biogas, the AD process produces digestate as a co-product, which can be used as fertilizer and dressing. Digestate contains valuable nutrients such as nitrogen, phosphorus and potassium that remain from the organic matter. The digestate makes better fertilizer than organic matter because some of the nutrients become easier for the plants to utilize through the AD process. (Kymäläinen and Pakarinen 2015, pp. 18)

2.2 Biomethane

Biomethane is produced by methanation or by upgrading biogas. Because it is almost pure CH_4, biomethane can be used along with natural gas. Figure 2.1 shows the pathways to produce biogas and biomethane. Biomethane can be used in the same applications as biogas. Yet due to its higher CH_4 content and heat value, it can also be used as a natural gas substitute. Biomethane is suitable for the transportation sector and can be injected into the gas network.(IEAa 2020)

2.2.1 Methanation

Methanation is a reaction where hydrogen (H_2) and carbon dioxide (CO_2) react and produce water (H_2O), methane (CH_4) and carbon monoxide (CO). Feedstocks for methanation can be produced from the gasification of biomass. The need for carbon monoxide depends on which methanation process is used. In gasification, H_2 and either CO_2 or CO are released and can be used as feedstock for methanation (IEAa 2020). H_2 can be produced by electrolysis, and CO_2 or CO can be removed from the atmosphere or provided by industries. The methanation process can be executed chemically with a catalyst or biologically with bacteria. (Savvas et al. 2017; Zoss and Blumberga 2016)

In chemical methanation, biomethane is produced with a catalyst. The process consists of three chemical reactions: methanation reaction (2.1), water gas transfer reaction (2.2) and Sabatier reaction (2.3). (Zoss and Blumberga 2016)

$$CO_2 + 3H_2 \leftrightarrow CH_4 + H_2O \tag{2.1}$$

$$CO_2 + H_2 \leftrightarrow CO + H_2O \tag{2.2}$$

$$CO + 4H_2 \leftrightarrow CH_4 + H_2O \tag{2.3}$$

In the biological methanation process, biomethane is produced using the enzymes of bacteria. During the reaction (2.4), the enzymes react with CO_2 and H_2 and produce CH_4 and H_2O (water). (Savvas et al. 2017)

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \tag{2.4}$$

The water can be removed so the CH_4 purity can be up to 98.9% (Patterson et al. 2017). The biomethane produced does not need any upgrading and can be used as is.

2.2.2 Biogas to biomethane

The most common way to produce biomethane is by upgrading biogas. The principle of biogas upgrading is to remove CO_2 from the biogas, thereby increasing the CH_4 of the upgraded biogas (biomethane) to 96–99%. There are various upgrading technologies. The most commonly used are physical absorption, chemical absorption, adsorption, membrane separation and cryogenic separation. (Angelidaki et al. 2018) The most commonly used upgrading technologies are introduced in Chapter 3.

3 BIOGAS UPGRADING

Raw biogas, such as landfill gases and biogas produced by anaerobic digestion from biomass, needs to be cleaned or upgraded in order to utilize the methane in it as a higher-grade product. Raw biogas contains many compounds that can degrade the properties of the gas. As we can see from Table 2.1, the lower heating value (LHV) is much lower in raw biogas than in natural gas. The main reason for the difference is the high CO_2 content in the biogas. By upgrading, the LHV increases, and the overall properties of biogas become better. This chapter discusses the operating principles and features of commercially used biogas upgrading technologies. (Khan et al. 2017; Sun et al. 2015)

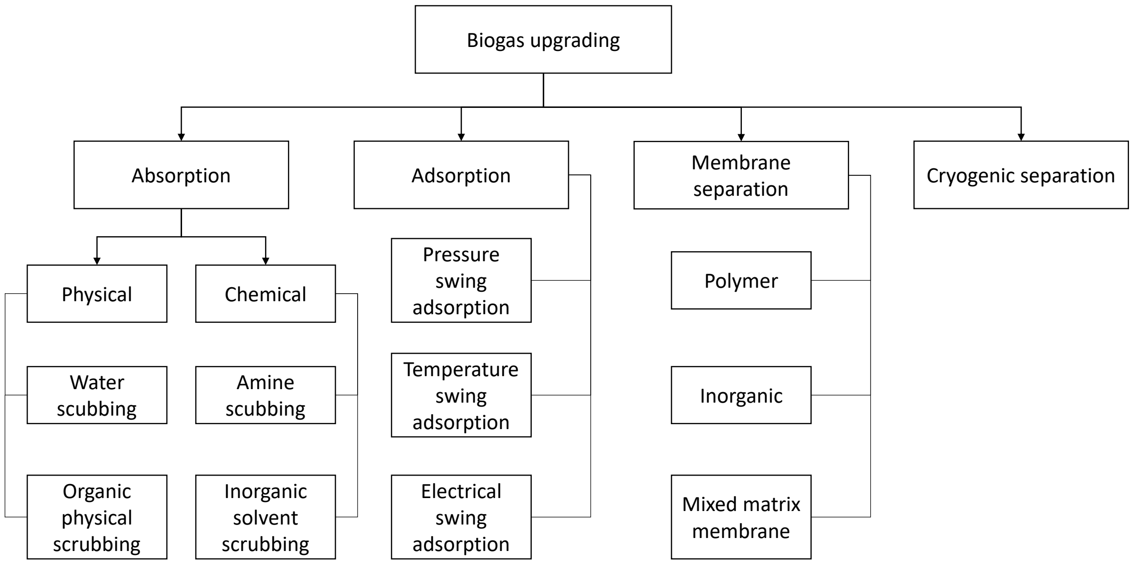

Figure 3.1. *Biogas upgrading technologies (Khan et al. 2017).*

Cleaning and upgrading both remove CO_2 and other harmful compounds such as nitrogen oxides, sulfurs and other impurities. However, cleaning and upgrading are different processes. Cleaning reduces the level of impurities, preventing damage to the equipment used in biogas upgrading and power generation. Impurities in combustion can cause corrosion, clogging, scaling and even explosions. Compounds such as CO_2 and nitrogen gas are not counted as impurities. Upgrading biogas increases the energy density of the biogas by removing inert gases such as CO_2 and nitrogen, which do not contain useful energy. (Kymäläinen and Pakarinen 2015, pp. 131) So by upgrading biogas, the energy density increases. Figure 3.1 shows the classification of commercially used biogas upgrading technologies.

Table 3.1. *Applicable common requirements and test methods for biomethane at the point of entry into the H and L gas networks in Finland (Kaasumarkkinat 2019; SFS-EN 16723-1 2016).*

Parameter	Unit	Limit values		Test method
		Min	Max	
Wobbe index	kWh/Nm^3	13.76	15.81	
Relative density		0.555	0.7	
Methane number		65		Annex A of EN 16726:2015
Total volatile silicon (as Si)	$mgSi/m^3$		0.3 (pure) to 1 (diluted)	EN ISO 16017-1:2000 TDS-GC-MS
Compressor oil		free from impurities		ISO 8573-2:2007
Dust impurities	mol-%	free from impurities		ISO 8573-4:2001
O	mol-%		0.02	
CO_2	mol-%		2.5	
CO	mol-%	-	0.1	EN ISO 6974- series
H_2S + COS	mg/Nm^3		5	
Mercaptan sulphur	mg/Nm^3		6	
Total sulphur	mg/Nm^3		21	
NH_3	mg/m^3		10	NEN 2826:1999 or VDI 3496 Blatt 1:1982-04 NF X43-303:2011
Amine	mg/m^3		10	VDI 2467 Blatt 2:1991-08
Water dew point	°C		-8	
Hydrocarbon dew point	°C		-2	

In order to receive a permit to supply biogas to the natural gas network, the biogas has to meet specific requirements. The SFS-EN 16723-1:2016 standard sets common requirements for biomethane quality in the European natural gas network. Countries may have different quality standards, but they have to meet the required SFS-EN 16723-1:2016 standard. Gas network owners can also set additional requirements for the gas that may not be required by the standards or may be country specific. In Finland, the owner of the gas network requires the gas to have at least 95% CH_4 content (Gasgrid 2020). In Denmark in 2017, the average CH_4 content in the gas network was 89.14% (Energinet 2020). The requirements in Finland are shown in Table 3.1.

3.1 Physical absorption

Physical absorption is a process where gas binds to a liquid or solid medium. The process is based on the solubility of the substances in the medium. Raw biogas contains many different substances with various solubilities. Physical absorption can be brought about either by water or chemical scrubbers that operate on the same principle, but use different solvents. (Khan et al. 2017; Kymäläinen and Pakarinen 2015, pp. 134-143)

3.1.1 Water scrubbing

Water scrubbing is the most common biogas upgrading technology according to Angelidaki et al. (2013). The operation of the water scrubber is based on the high solubility of CO_2 compared to that of CH_4. CO_2 solubility is 26 times higher than the solubility of CH_4, which allows efficient separation of CO_2 from biogas with small CH_4 losses (Angelidaki et al. 2018). Effective water scrubbing removes hydrogen sulfides, ammonia and methyl mercaptan from the biogas. According to Sun et al. (2015), biogas upgrading with water scrubbers can achieve a CH_4 purity of 80–99%, depending on the volume of nitrogen and oxygen. The drawback of a water scrubber is its low nitrogen-removing capability due to nitrogen's low water solubility. A small amount of CH_4 dissolves into water, lowering the methane content of the biomethane produced. The amount of CH_4 dissolved, or lost, is usually 3–5% according to theoretical calculations, but some water scrubber suppliers claim to achieve lower than 2% losses (Sun et al. 2015). Even though part of the methane will dissolve in water, it can be recovered back as raw biogas. The solubility can be calculated with Henry's law equation.

$$c_a = k_h * p_g, \tag{3.1}$$

where c_a is concentration in water, k_h is Henry's law constant and p_g is gas partial pressure. Henry's law constant depends on temperature, pressure and type of gas. As temperature rises, the solubility generally decreases. Increasing pressure increases solubility. (Kymäläinen and Pakarinen 2015, pp. 140)

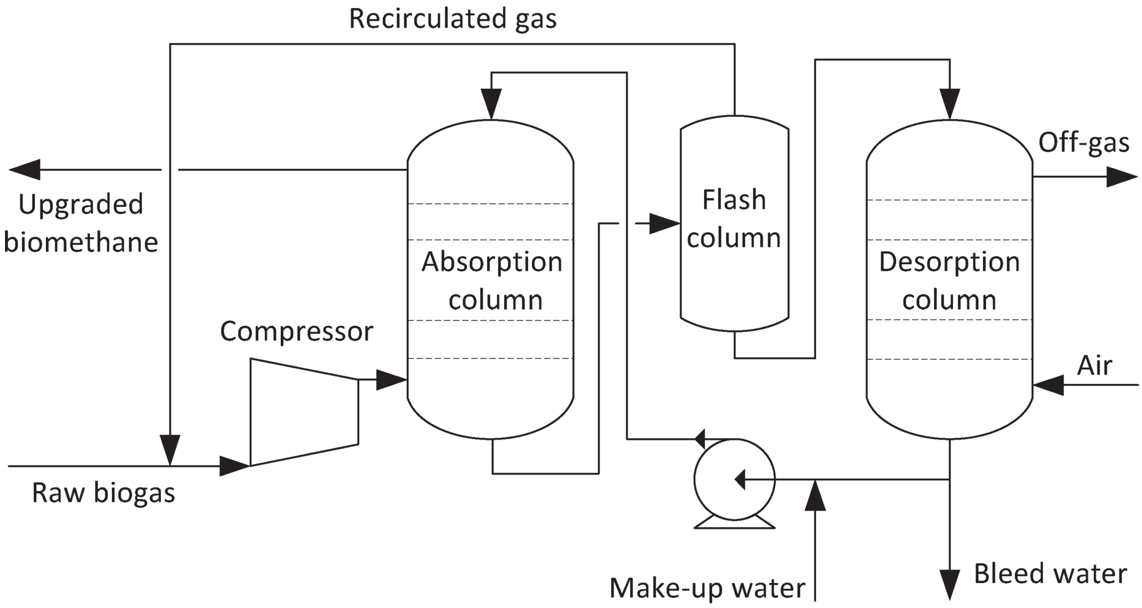

Figure 3.2. *Simplified process flow diagram of a recirculating water scrubber (Bauer, Persson et al. 2013).*

Figure 3.2 shows a process flow diagram of the commonly used water scrubber system. Raw biogas is pressurized in a compressor to 6–10 bar and temperature can increase up to 40 °C. In some cases, raw biogas can be pressurized up to 150 bar (Kymäläinen and Pakarinen 2015, pp. 142). Pressurized biogas is injected into the absorption column from the bottom and water is fed from the top, until they make a counterflow contact. Upgraded biogas is released from the top of the scrubber and needs to be dried before use. Water is fed into the flash column where the pressure is decreased quickly to 2.5–3.5 bar. In the flash column, most of the dissolved CH_4 is removed by a pressure change and recirculated back to raw biogas. From the flash column, water is fed into the desorption column from the top and air is injected into the bottom. In the desorption column, pressure decreases to atmospheric pressure at which point CO_2 and H_2S are removed from the water with air as off-gas. If the off-gas contains more impurities than the environmental permissions allow, the off-gas must be purified (Kymäläinen and Pakarinen 2015, pp. 142). In certain situations, the desorption column is not needed. One example is in sewage treatment plants where the water can be purified with existing equipment. Part of the water is mixed with new water to minimize impurities and then circulated back into the absorption column. (Ryckebosch et al. 2011) Both absorption and desorption columns are equipped with random packing material to increase the specific surface for gas-liquid contact. The packing material will become dirty and needs to be replaced periodically (Kymäläinen and Pakarinen 2015, pp. 142).

To upgrade 1,000 m^3/h of raw biogas in standard temperature and pressure (STP) conditions usually needs 200 m^3/h of circulating water if operated at 8 bar and 20 °C. Decreasing the water temperature will decrease the need for water flow through the absorption column. However, the decreasing operating pressure will increase the need for water flow. The required water flow depends on the total gas flow through the absorption column. The methane content of raw biogas does not affect the water flow rate. The operating temperature and pressure depend on the solubility constant of CO_2. (Bauer, Persson et al. 2013) Even though water is purified in the process, a small number of impurities — such as H_2S – remain. The impurities decrease the pH of water in the long term. New water needs to be added to the system, and according to Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. (2019a) average water consumption is 0.5–5 m3/day. Research shows that to achieve the highest CH_4 content in upgraded biogas, the ideal gas-to-water ratio is nine (Nie et al. 2013). Water consumption depends on the scale of the plant and how effectively the water is purified in the process. Bacteria growth can cause clogging (Khan et al. 2017).

3.1.2 Organic physical scrubbing

The operating principles of organic physical scrubbers (OPS) are almost the same for water scrubbing, but the solvent liquid is different, and there are some changes in the process. Figure 3.3 shows a typical OPS flow diagram. The absorbent liquid is chosen so that the solubility of CO_2 is higher than that of water. Solubility can be calculated with Henry's law equation 3.1, which is explained in Chapter 3.1.1. (Kymäläinen and Pakarinen 2015, pp. 143) Due to higher solubility, the scrubbing equipment is smaller, solvent demand is lower and less pumping power is needed. As a result, investment costs are lower. However, the purchase and treatment cost of chemicals is higher than in a water scrubber (Kymäläinen and Pakarinen 2015, pp. 143). Kymäläinen and Pakarinen (2015, p. 143) also claim that OPS electricity demand is lower, while Khan, Othman and Hashim (2017) maintain that regenerating solvent requires more energy than is needed in water scrubbing. The most commonly used solvents are methanol, N-methyl pyrrolidone and polyethylene glycol ethers (Khan et al. 2017). Chemicals used for scrubbing are mixtures of chemicals. The most commonly used commercial liquids are Genosorp®, Selexol®, Coastal AGR®, Rektisol®and Purisol®(Kymäläinen and Pakarinen 2015, p. 143; Miltner, Makaruk and Harasek 2017).

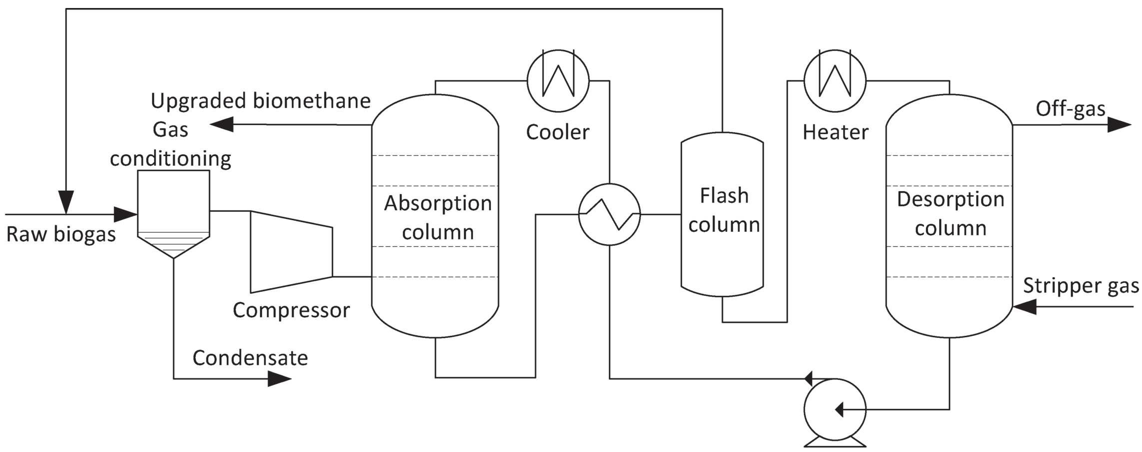

Figure 3.3. *Simplified process flow diagram of an organic solvent scrubber (Bauer, Persson et al. 2013).*

Organic physical scrubbers have the same operating principles as water scrubbers, and biogas and the organic solvent are circulated almost in the same way. Raw biogas is pressurized to 6–8 bar and cooled to around 20 °C before entering the absorption column (Bauer, Persson et al. 2013). Organic solvent leaves from the absorption column and goes through a heat exchanger. The heat exchanger heats the organic solvent on its way to the flash column and cools the solvent going back to the absorption column. From the flash column, the solvent is heated to 40–80 °C (Khan et al. 2017; Sun et al. 2015). The temperature depends on Henry's laws constant. Next, the solvent goes to the desorption column, then through a pump and heat exchanger to a cooler, where it is cooled to the right temperature before it re-enters the absorption column. As before, the temperature depends on Henry's laws constant. (Khan et al. 2017) A detailed description of the operations in the absorption, flash and desorption columns is given in Chapter 3.1.1.

Organic solvents used in the OPS system do not cause corrosion, so pipework can be made of cheaper material than stainless steel. Organic solvents have a lower freezing point than water, so the scrubbers can be operated in colder temperatures without the need for extra heating. According to Kymäläinen and Pakarinen (2015, p. 137), CH_4 purity is greater than 96% and methane leaks are less than 1%.

3.2 Chemical absorption

In chemical absorption, biogas is upgraded using reagents that chemically bind CO_2, H_2S molecules and other compounds, and remove unwanted compounds from the biogas (Bauer, Persson et al. 2013). Chemical absorption can be divided into amine and inorganic solvent scrubbing. Amine scrubbing uses organic compounds such as diethanolamine, monoethanolamine or methyl diethanolamine. Inorganic solvent scrubbing uses compounds that contain aqueous solutions, for instance, sodium, potassium, ammonium, or calcium hydroxide. (Khan et al. 2017) Due to high selectivity in amine scrubbing, CH_4 purity can be up to 99% and CH_4 losses can be less than 0.1%. Sun et al. (2015) write in their paper that CH_4 loss is 0.1–0.2% in a plant with a capacity of 300 Nm^3/h. Amine solvents are more typically used than inorganic solvents in chemical scrubbing due to the higher solubility of amine.

3.2.1 Amine scrubbing

Figure 3.4 shows the simplified flow diagram of an amine scrubber. Raw biogas enters the absorption column from the bottom, and an amine or inorganic solution is supplied from the top to make contact in a counter-current flow. The operating pressure of the absorbers is 1–2 bar. In the absorption column, CO_2 and H_2S react with the solution and are absorbed in the liquid phase. The absorbing reaction is exothermic, so the temperature of the solvent will increase from 40–45 °C to 45–65 °C. The solubility of CO_2 and H_2S can be increased by increasing the temperature. (Bauer, Persson et al. 2013) According to Khan, Othman and Hashim (2017), a higher temperature subsequently allows more CO_2 and H_2S to be absorbed. Upgraded biomethane leaves as a gas from the top of the column, and the remaining liquid is pumped through a heat exchanger to the top of the stripper column. The heat exchanger heats the liquid before the stripper column using stripper's exit stream. In the stripper column, the liquid is in contact with steam, and CO_2 and H_2S are separated from the liquid. The released CO_2 and H_2S leave as a gas from the top of the column. At the bottom of the stripper column, a reboiler heats the amine solution to the boiling point at 120–150 °C. The reboiler provides heat for the reaction to release CO_2 and H_2S from the amine solution and regenerate the amine solution (Khan et al. 2017). The heat from the reboiler generates steam that has a lower partial pressure than CO_2 and H_2S in the column. The lower partial pressure improves the kinetics of desorption. The pressure in the stripper column is typically 1.5–3 bar. (Bauer, Hulteberg et al. 2013; Bauer, Persson et al. 2013)

According to Bauer, Hulteberg et al. (2013), the heat supplied to the reboiler can be hot water, oil or steam. They write that in some cases the stripping column operates under

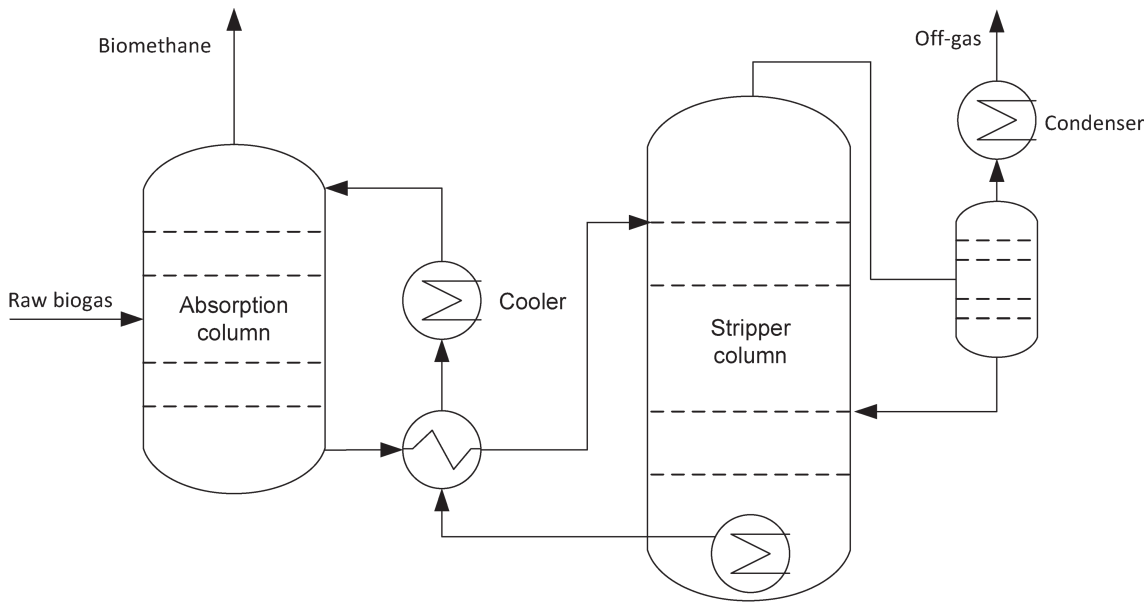

Figure 3.4. *Simplified process flow diagram of an amine scrubber (Bauer, Persson et al. 2013).*

vacuum, and the heat source is district heat at 90 °C. The released steam, CO_2 and H_2S mixture leave from the top of the stripper column and go on to the condenser. There, the condensate is mainly composed of steam. Any traces of amine are returned to the stripper column.

In most processes, 1 mole of amine is needed for 0.5–1.0 mole of CO_2 (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a). The amount of amines needed varies according to which organic compound is used. For example, a theoretical amount of monoethanol to capture 1 ton of CO_2 is 1.39 tons (Yoo et al. 2013). The advantages of amine scrubbing are high selectivity, high reduction of volume compared to other upgrading methods and low operating costs. Due to the high pH of amine solutions, bacteria growth is not a risk (Bauer, Hulteberg et al. 2013). Therefore, it is easy to use packing material inside the columns to improve the reactions between compounds. The disadvantages of amine scrubbing are that the solvent used is toxic to humans and the environment, high investment costs, high heat requirements to regenerate chemical solutions, the high cost of amine solvents and a loss of amine solvents due to evaporation (Angelidaki et al. 2018). Therefore, alkaline salts can be a better option because they are lower priced and are also more abundant than amine solvents (Yoo et al. 2013). According to Khan, Othman and Hashim (2017), to desorb H_2S from amine solutions, even higher temperatures are needed. They recommend removing the H_2S as early as in the anaerobic digestion process. Other drawbacks include the foaming precipitation of salts, decomposition of the amines or poisoning that can occur due to O2 and other compounds (Chen et al. 2015).

3.2.2 Inorganic solvent scrubbing

In inorganic solvent scrubbing, CO_2 is converted to carbonated salts through precipitation by compounds with alkaline character (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a). The solvent is usually an aqueous solution of alkaline salts. For example, the theoretical amount of sodium hydroxide is 0.9 tons to capture 1 ton of CO_2 (Yoo et al. 2013). To improve the solution, turbulence is used to create maximum contact between CO_2 and the solution. The main advantages of inorganic scrubbing are that solvents are environmentally friendly and alkaline salts are cheaper than amine solvents. The disadvantage is that the CH_4 purity is not as high as with amine scrubbing. (Khan et al. 2017) Inorganic solvent scrubbing is not widely used upgrading technology in biogas upgrading, and as a result, not much research or information is available.

3.3 Physical adsorption

In physical adsorption, gas components are removed from the gas by a porous medium (Kymäläinen and Pakarinen 2015, pp. 145). The process effectively removes CO_2 and other impurities. Still, choosing the right adsorbent is essential to efficient upgrading. The material should have good moisture removal capacity and be easily regenerated with low energy consumption. Commonly used molecular sieve materials are zeolites, titanosilicates, silica gels and activated carbon (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a). The porous materials are moderately easy for CO_2 molecules to penetrate while retaining CH_4 molecules. Effective separation is a result of different sizes of molecules and their adsorption capacity. The material should have good moisture removal capacity and be easily regenerated with low energy consumption. There are three main types of physical adsorption technologies: pressure swing adsorption (PSA), temperature swing adsorption (TSA) and electrical swing adsorption (ESA). (Khan et al. 2017)

3.3.1 Pressure swing adsorption

The most commonly used physical adsorption technology is pressure swing adsorption (PSA) (Angelidaki et al. 2018). As shown in Figure 3.5, H_2S has to be removed from the biogas before entering adsorption columns because the adsorption material adsorbs H_2S irreversibly. Therefore, it is considered toxic to adsorption materials (Sun et al. 2015). Also, moisture needs to be removed before entering the columns (Kymäläinen and Pakarinen 2015, pp. 146). The PSA unit usually consists of four phases: pressurization, feed, blowdown and purge. In the feed phase, biogas is pressurized to 4–10 bar and injected into the adsorption column. In the adsorption column, the CO_2 adsorbs to the column bed and CH_4 goes through the column. The gas stream continues to the next column when the column bed is saturated with upgraded biogas (Angelidaki et al. 2018). The saturated column bed is restored in the blowdown phase. The CO_2 is desorbed from the adsorbent by decreasing pressure to ambient or lower pressure inside the column in this phase. Desorbed CO_2-rich gas is released from the column. The columns are repressurized with raw biogas or with upgraded gas, increasing the energy efficiency of the process. CH_4 losses will occur with the desorbed CO_2 gas mixture. To minimize the CH_4 losses, the desorbed CO_2 gas mixture is circulated back to the PSA inlet (Angelidaki et al. 2018). One of the columns is always in the adsorption phase and the others are in a different phase of regeneration. To achieve continuous operation in PSA, there are usually two or four columns. (Bauer, Persson et al. 2013)

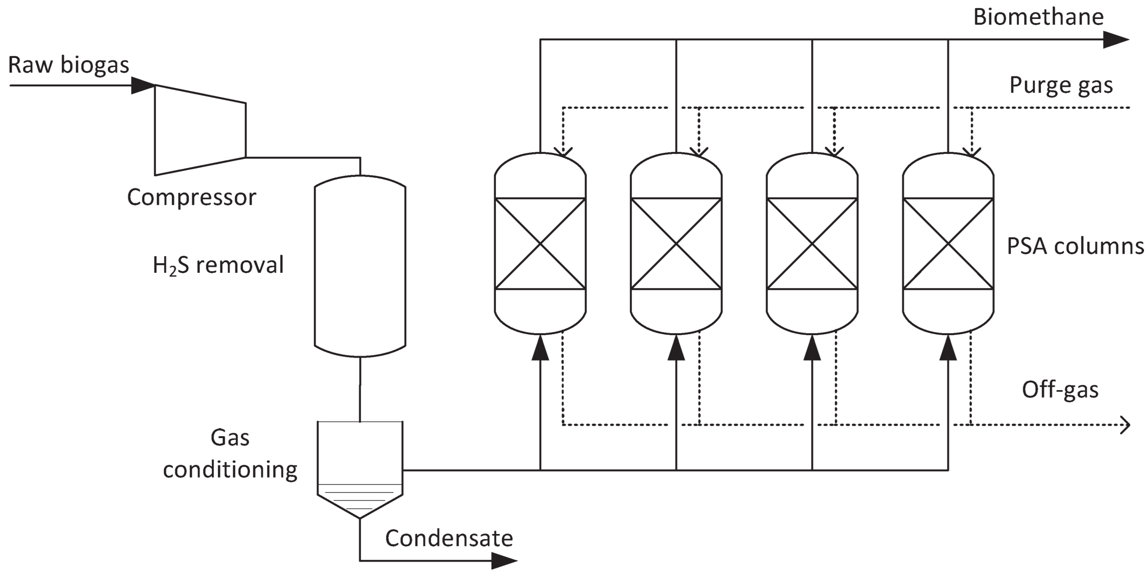

Figure 3.5. *Simplified process flow diagram of a pressure swing adsorption unit (Bauer, Persson et al. 2013).*

PSA can achieve up to 96–98% CH_4 content while the CH_4 loss is 2–4% (Bauer, Hulteberg et al. 2013). The advantages of the technology are compactness of the equipment, low capital cost, low energy consumption, safety and simplified operation. (Augelletti et al. 2017) The process does not need water, which can be an important factor in some countries. Disadvantages of PSA are low CH_4 purity of upgraded biogas compared to other upgrading technologies and high CH_4 losses. Sun et al. (2015) discussed in their paper that in two PSA biogas upgrading plants, CH_4 losses have been 10–12%, even though the equipment suppliers claim that CH_4 losses are below 2%. Due to high CH_4 losses in some cases, the off-gas has to be purified of CH_4 before being released to the atmosphere (Augelletti et al. 2017). According to Kymäläinen and Pakarinen (2015, p. 146), nitrogen cannot be removed because its molecular size is near the size of the CH_4 molecule. So, the upgraded gas contains at least 4% nitrogen. Augelletti, Conti and Annesini (2017) made a study where two PSA units were integrated. In their study, they used Zeolite 5A as the adsorbent material and achieved a methane recovery rate greater than 99% with an energy consumption of about 1250 kJ/kg of biomethane. Energy consumption in the Augelletti, Conti and Annesini (2017) study was 0.23 kWh/m^3. The calculations were made with the assumption that upgraded biogas is 100% CH_4. Energy consumption with Carbotech's PSA upgrading technology is 0.21–0.23 kWh/m^3. The CH_4 content in upgraded biogas is more than 99% (Carbotech 2016). Energy consumption is relative to the size of the upgrading plant. Therefore, energy consumption decreases when the capacity of the upgrading plant increases.

3.3.2 Temperature swing adsorption

Temperature swing adsorption (TSA) operating principles are the same as in PSA, but while PSA uses pressure changes to adsorb biogas, TSA uses temperature changes. With TSA, the temperature changes from 40 to 120 °C in atmospheric pressure (Miltner et al. 2017). Adsorption occurs in lower temperatures and desorption in higher. Temperatures depend on the properties of the adsorbent material. In the Vogtenhuber et al. (2017) paper, they calculated that the optimal temperature range is 45–100 °C. CO_2 capture rate was 96% in their simulations. As adsorption is an exothermic process, it requires cooling to maintain the right temperature for adsorption. However, the desorption process is endothermic. Therefore, it needs the same amount of heating energy as adsorption needs cooling energy. Heat transfer between the adsorption and desorption columns is an important feature, lowering the energy demand in the process. (Vogtenhuber et al. 2017) In TSA, the adsorbent is more effective than in PSA, but slow heating and cooling are disadvantages (Zhou et al. 2017). According to Kymäläinen and Pakarinen (2015 p. 146), TSA upgrading is not used in biogas upgrading, but instead is used for biogas purification, especially for the removal of water.

3.3.3 Electrical swing adsorption

Electrical swing adsorption (ESA) is the same process as TSA, but in ESA, the heat is created with the Joule effect by passing electricity through conductors. In ESA, the adsorbent is heated much faster. Therefore, no other gas is needed to increase the temperature. ESA requires a significant amount of electricity, so it is not economical alone. However, the ESA-TSA hybrid process is an alternative worth considering. (Zhou et al. 2017)

3.4 Membrane separation

Membrane separation is based on the separation of different size molecules. CO_2 and H_2S are smaller molecules than CH_4, so CO_2 and H_2S permeate through the membrane, while CH_4 does not. (Sun et al. 2015) H_2S and water can be separated from biogas with membranes, but it is desirable to remove H_2S and water before the membrane because H_2S and water can cause corrosion (Angelidaki et al. 2018). The efficiency of the CO_2 separation is strictly dependent on the type of membrane. Most commercially used membranes are composed of polymers from organic materials such as polycarbonate or cellulose acetate (Angelidaki et al. 2018; Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a).

As shown in Figure 3.6, H_2S and water are removed from the biogas, which is then compressed to 8–40 bar before being injected into the membrane unit (Angelidaki et al. 2018; Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a). CO_2 permeates through the membrane, and CH_4 remains on the side of high pressure. According to Baena-Moreno et al. (2019), this reduces the needed pressurization when CH_4 is distributed to the natural gas network or gas containers because the biomethane is already pressurized. The off-gas is recirculated to achieve lower CH_4 losses. (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a)

Membrane separation can be implemented with different designs. The three most common designs are shown in Figure 3.7. The first design (i) contains only one membrane and has no recirculation. Energy consumption and maintenance are lower in the first design, but methane losses are higher than in other implementations. Therefore, choosing the right membrane with high selectivity for this design is important (Angelidaki et al. 2018; Bauer, Hulteberg et al. 2013) The second design (ii) uses two membranes and

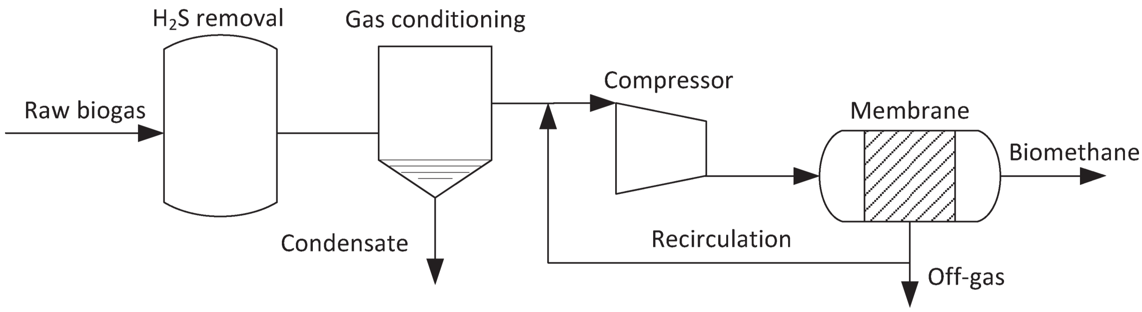

Figure 3.6. *Simplified process design of a membrane separation process (Bauer, Persson et al. 2013).*

recirculation to reduce CH_4 losses and increase CH_4 purity in upgraded biogas. In the third design (iii), there are three membranes. The operating principle is the same as in design two (ii), but in design three (iii), the waste gas (off-gas) goes through a membrane to achieve lower CH_4 losses. (Bauer, Hulteberg et al. 2013)

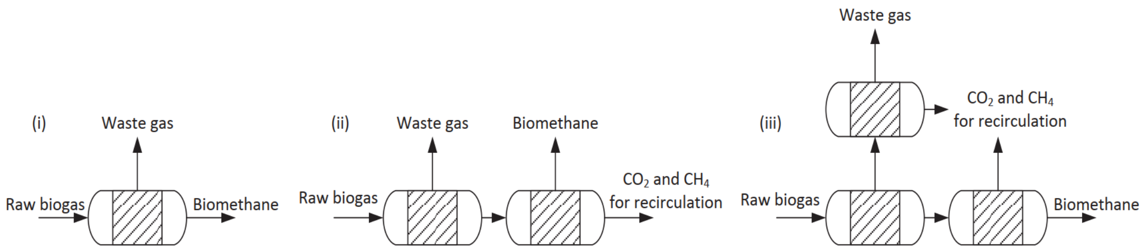

Figure 3.7. *Membrane separation designs (Bauer, Hulteberg et al. 2013).*

Membrane separation can be performed in a dry or wet process. The dry process uses only membranes to upgrade biogas. In the wet process, microporous membranes with hydrophobic properties are used, combining the advantages of absorption technologies. In the wet process, the membranes separate the gas from the liquid, and gas molecules go through the membrane. The absorption occurs with liquid media that flows in a direction counter to the gas flow. Regeneration of the solution liquid occurs under high temperature. The disadvantages of the wet process are the high cost and frangibility of the membranes. (Angelidaki et al. 2018)

The different types of membranes are polymeric, inorganic and mixed matrix membranes (MMM). Polymeric membranes are the most commonly used in commercial upgrading plants. Polymeric membranes are made of organic material such as polysulfone, polyimide, polycarbonate, polydimethylsiloxane or cellulose acetate. Polyimide and cellulose acetate membranes are the most typically used polymeric membranes. The advantages of polymeric membranes are high mechanical strength, low cost and high selective permeation. Some polymeric membranes have low plasticization pressure, which means the pressure is not optimal for reducing CH_4 losses. The plasticization pressure of cellulose acetate is 0.8 MPa. Matrimid®– a commercially available polyimide – has a plasticization pressure of 1.7 MPa. Polysulfone membranes have an ever higher plasticization pressure of 3.4 MPa, but their separation properties are not as good as those of cellulose acetate and polyimide membranes. (Khan et al. 2017; Sun et al. 2015)

The most typically used inorganic membranes are zeolite, activated carbon, silica, carbon nanotubes and a metal-organic framework. They offer more mechanical strength, thermal stability and resistance to chemicals than polymeric membranes. The inorganic membranes exceed the Robeson upper bound. (Khan et al. 2017) The empirical upper bound relationship for membrane separation gases can be calculated using Robeson upper bound (Robeson 2008). Robeson upper bound correlates the relationship between permeability and selectivity and can be calculated as follows:

$$P_i = k * \alpha_{ij}^n, \tag{3.2}$$

where P_i is the permeability of the fast gas, k is the front factor, α_{ij} is the separation factor and n is the "slope of the log-log plot of the noted relationship." (Robeson 2008) Problems with inorganic membranes stem from their fabrication. The fabrication process requires continuous monitoring because of the membranes' fragile structure. Rigid porous membranes, such as carbon and zeolites molecular sieves, suffer from uneven porosities that affect their biogas separation capability. (Khan et al. 2017)

Mixed matrix membranes are membranes that contain both polymeric and inorganic materials. The polymeric materials form a continuous phase, and inorganic particles form a dispersed phase. With mixed matrix membranes, the goal is to combine the benefits of polymeric and inorganic membranes and overcome their limitations. The polymeric membranes have high processability and lower processing costs, while inorganic membranes have better separation performance. (Khan et al. 2017)

CH_4 losses can be reduced by recirculating the off-gas. Higher CH_4 content can be achieved by using more than one membrane, a larger membrane area or higher process pressure. The CH_4 recovery can be up to 99.5% in raw biogas with a CH_4 content of 80%. (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a; Bauer, Persson et al. 2013) Nitrogen can be separated from biogas, but it requires another membrane because CH_4 and nitrogen molecules are almost the same size. Due to the similarity in molecular sizes, upgraded biogas will have at least a few percent nitrogen if the raw biogas contains nitrogen (Kymäläinen and Pakarinen 2015, pp. 149). The energy consumption is 0.20–30 kWh/Nm^3, and the estimated lifespan of the membranes is 5–10 years (Bauer, Hulteberg et al. 2013).

3.5 Cryogenic separation

Cryogenic separation is based on the different condensate temperatures of the different gases contained in raw biogas. The raw biogas is cooled and compressed to a specified degree so the desired compound condenses and can be separated as a liquid. At 101.325 kPa (1 atm), the condensate temperature of CH_4 is 161.5 °C and the boiling point of CO_2 is 78.2 °C (Khan et al. 2017). Removing water and H_2S from the biogas before upgrading is recommended to avoid freezing and clogging (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a; Sun et al. 2015).

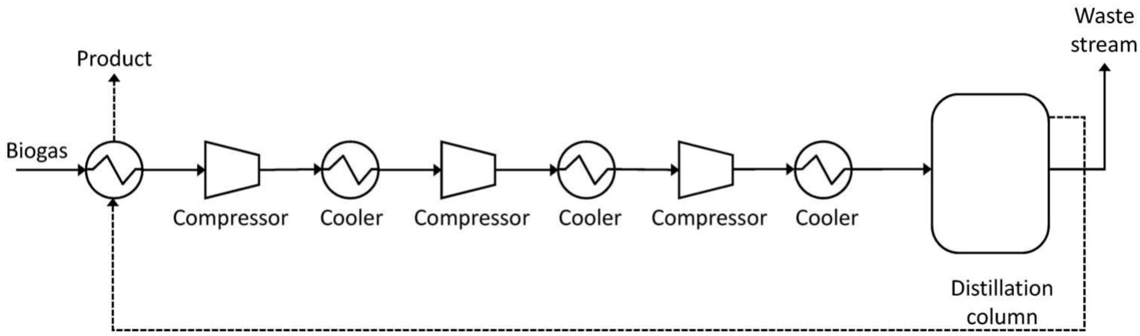

Figure 3.8. *Simplified process design for a cryogenic separation process (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a).*

Separation occurs by pressurizing and cooling the biogas in steps. Typical operating parameters according to Baena-Moreno et al. (2019) are 8.0 MPa and -170 °C. According to Ryckebosch, Drouillon and Vervaeren (2011), the parameters are 8.0 MPa and -110 °C. According to Sun et al. (2015), the pressure can be up to 20 MPa. Separation needs to be pressurized because CO_2 does not condense in atmospheric pressure (Kymäläinen and Pakarinen 2015, pp. 148). After pressurizing and cooling the biogas to the specified temperature, the biogas goes to a distillation column where it is separated. CO_2 is separated from biogas in the liquid phase. Nitrogen can be separated from biogas by cooling it to methane's condensation temperature. CH_4 condenses to a liquid and nitrogen stays as a gas (Kymäläinen and Pakarinen 2015, pp. 148).

With cryogenic separation, CH_4 purity can be up to 98% and CH_4 losses can be less than

1% (Sun et al. 2015). The separated CO_2 purity is 99.9%. As it is in the liquid phase, the CO_2 can easily be used for other applications (Baena-Moreno, Rodríguez-Galán, Vega, L. Vilches et al. 2019b). Cryogenic separation is the best upgrading technology for producing liquefied biogas (LBG) (Khan et al. 2017). Its disadvantages of cryogenic separation are high energy consumption, high capital cost and the need for biogas purification before upgrading (Baena-Moreno, Rodríguez-Galán, Vega, L. Vilches et al. 2019b). Energy consumption is 0.8 kWh/Nm^3 with a biogas flow rate of 50–2400 Nm^3/h (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a; Yousef et al. 2018). The process can be combined with other upgrading technologies to achieve the highest upgrading capacity and to keep impurities such as water and H_2S from entering the cryogenic equipment (Baena-Moreno, Rodríguez-Galán, Vega, L. Vilches et al. 2019b).

3.6 Off-gas treatment

The off-gas from a biogas upgrading plant may need treatment before entering the atmosphere, depending on the composition of the off-gas and national legislation. Harmful contaminants in the off-gas are CH_4, H_2S and SO_X. The most commonly used methods to remove CH_4 from off-gas are regenerative thermal oxidation, catalytic oxidation, flameless oxidation and co-firing in combustion engines. H_2S is usually removed from the off-gas with active carbon filters, while SO_X is removed with chemical scrubbing. (Wellinger et al. 2013, pp. 365-366)

4 CARBON DIOXIDE CAPTURE AND UTILIZATION

Capturing carbon dioxide before it enters the atmosphere prevents climate change, and the captured CO_2 can be sold. Although carbon capture and utilization technologies have existed for a while, carbon capture has not become widely used. (Jones et al. 2014) Carbon dioxide is currently being used in many applications — agriculture, mineral carbonation, oil and gas recovery, as well as chemical products such as urea, methanol and methane, to name a few. (Bui et al. 2018; Commission 2018) Still, new applications, such as power-to-X solutions, are constantly being developed.

Carbon capture and utilization (CCU) is still in the infancy state and very energy-intensive. However, governments, industry and investors are interested in CCU. Carbon dioxide capture and utilization is still low compared to the annual production volume of CO_2. In 2019, global CO_2 emissions were 33 Gt and captured CO_2 was 35 Mt/a from power and industry facilities. IEA estimates that with a sustainable development scenario, captured CO_2 should increase to 350 Mt/a in 2030 and 1488 Mt/a in 2040. (IEAb 2020; IEAc 2020) The CO_2 consumption was 230 Mt/a in 2015 (IEA 2019). In the future, CO_2 will be utilized in many applications and will be a valuable raw material for industry.

4.1 Carbon capture from biogas upgrading plants

Carbon capture in biogas upgrading plants is part of the biogas upgrading process discussed in Chapter 3. CO_2 is separated from the biogas in the upgrading process. In most of the upgrading technologies, CO_2 is fed out in off-gas, with CO_2 in the gas phase. The off-gas may also contain other compounds, such as H_2S and N_2 (Khan et al. 2017). The amount of these compounds depends on the purification degree of the raw biogas and the upgrading technology used. Some degree of methane loss is always present in upgrading technologies, which can affect the utilization of CO_2. In cryogenic separation, the captured CO_2 is in liquid form, which improves its handling, storage and utilization of CO_2. (Sun et al. 2015)

4.2 Utilization

CO_2 can be utilized in many applications, and new applications are being developed all the time. CO_2 is utilized primarily in two ways: conversion and non-conversion. In conversion utilization, the captured CO_2 is converted into products through multiple chemical and biological processes. In non-conversion utilization, captured CO_2 is used as it is. (IEA 2019) Figure 4.1 shows some of the different utilization options for CO_2.

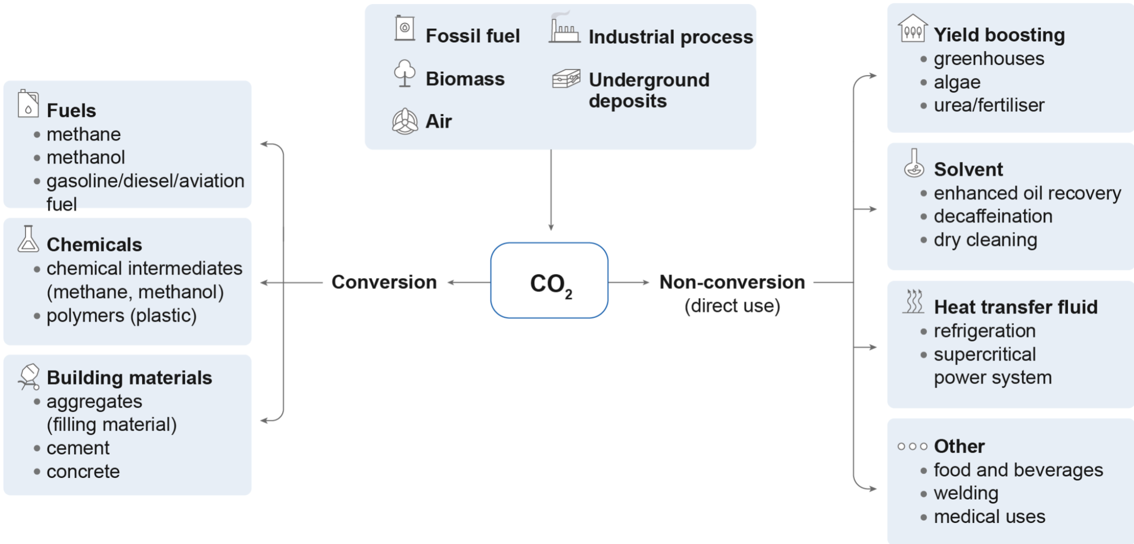

Figure 4.1. *Utilisation options for CO_2 (IEA 2019).*

Captured CO_2 can be converted into fuels such as methane and methanol and other types. Using renewable energy sources to create renewable fuels from CO_2 might be a potential energy storage method in the future. This method is known as power-to-X. The principle of power-to-X is to produce fuels using low-cost renewable electricity. Principles of the methanation process, where CO_2 and H_2 are converted into CH_4 and H_2O, are introduced in Chapter 2.2.1. The problem with CO_2-based fuels is that capital and production costs can be several times higher than for fossil fuels because hydrogen is energy-intensive to produce and the necessary equipment is expensive. However, the production cost is expected to come down. CO_2 can be used to produce plastics, fibers, synthetic rubber, health and hygiene products, and chemicals for food production and processing. CO_2 can provide an alternative raw material to fossil fuels. Building materials, such as aggregates, cement and concrete, can be produced with CO_2 which replaces water in concrete production using a process called CO_2 curing. (IEA 2019)

In non-conversion applications, CO_2 can be used as it is. These applications are introduced in Figure 4.1. Currently, CO_2 is primarily used in urea manufacturing. In 2015,

CO_2 consumption was 230 Mt/a, of which 57% of the total CO_2 consumption was used to produce urea and 34% for enhanced oil recovery. CO_2 can be also injected into greenhouses to improve photosynthesis, used as heat transfer fluid or in other industrial uses. (IEA 2019)

5 AUTOMATION

Automation means actions that take place without direct human intervention. Automation has a significant role in industry nowadays. It is used to improve product quality, production capacity, safety, energy efficiency and to reduce environmental impact. The operation of a process is usually most effective when it is consistently near some limit. This limit can be, for example, a set temperature or pressure limit. Automation helps to keep the process as close to the limit as possible. Responding rapidly to changes in a process can have a significant impact. Faster responses can increase productivity and decrease errors. With automation, a dangerous task can be handled remotely, without people being close to the operation. (Tekes 2005)

5.1 Automation in industry

Industry automation can be divided into manufacturing and process automation. Manufacturing automation specializes in handling distinguishable parts to assemble products and focuses on the handling of fluids, gases and sludges. (Oulu.fi 2014) Process automation uses many computers to communicate with each other through networks, actuators, sensors and transmitters. Typically, an automation system transforms analog signals – typically 4–20 mA – from sensors by using measuring transmitters into digital signals in the automation system's process interface units. The digital data is easy for a computer to process. The computers get real-time data from the sensors and can manipulate the actuator to control the process as needed. (Budampati and Kolavennu 2016, pp. 39)

5.2 Automation system

An automation system consists of an I/O interface, field devices, automation functions, such as logic, control and regulation functions, calculation and reporting, and a man-machine interface. The field devices consist of sensors, transmitters, limit switches, actuators and cabling. (Oulu.fi 2014)

A centralized control system (CCS) is controlled by one master controller and several slave controllers. The master controller makes decisions and controls the slave controllers, which operate the field devices. Problems with the CCS are a long computation time and single-point failures. (Chauhan and Saini 2014)

A programmable logic controller (PLC) is a computer-based, single-processor device that is used to control processes in real time. The PLC can be used in binary logic and continuous control and is used to control many types of industrial instruments. PLCs are efficient and reliable. They can be used in manufacturing, chemical and process industries. They are most often used to execute the logic of the system. The price of a complex and advanced level control system can decrease if a PLC is used. (Alphonsus and Abdullah 2016)

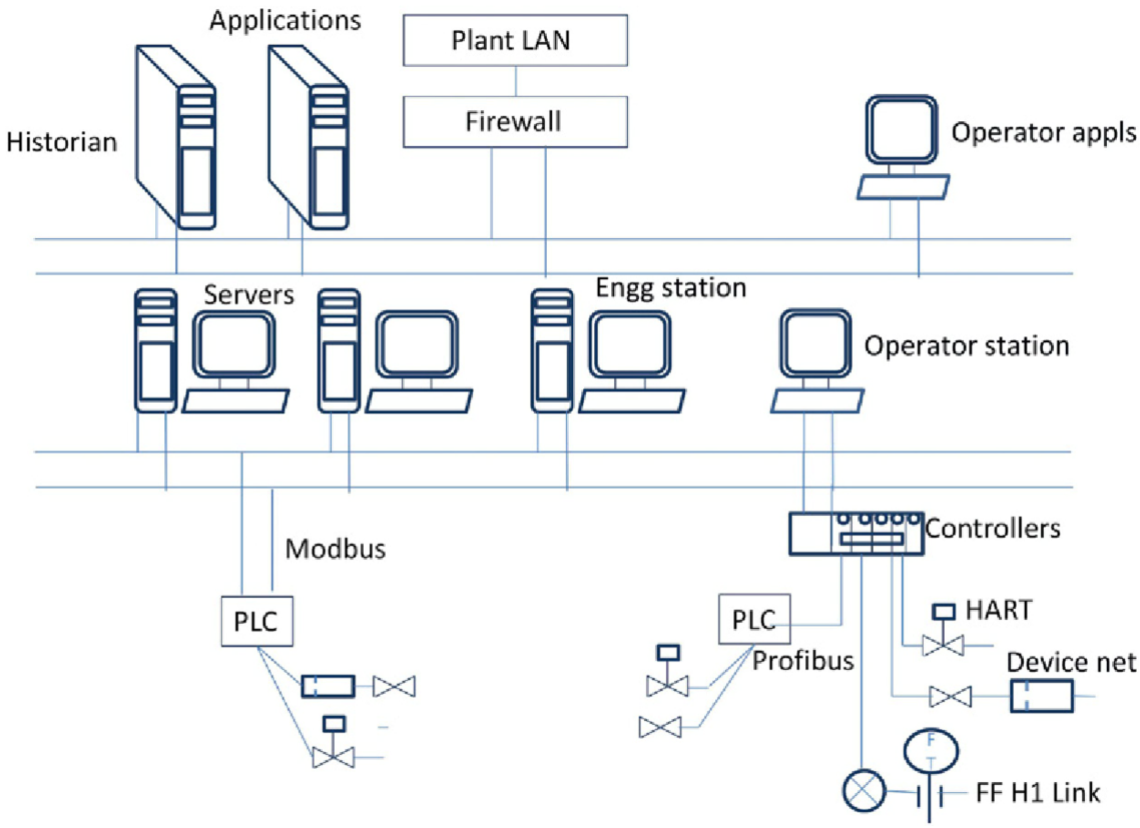

Figure 5.1. *Architecture of a simple DCS (Mehta and R. 2015, p. 82)*

A distributed control system (DCS) is a computer-controlled automation system for industry. The control occurs in microprocessor-based process stations, or in some cases, in the field device itself. These process stations can be PLC units that have been integrated with the DCS. Using the DCS, the operator can monitor and control the process from a distance. The problem with a DCS is the complex communication system among the local controllers (Chauhan and Saini 2014). As a DCS can be connected to the internet, cybersecurity is essential to continuous and safe operation. Figure 5.1 illustrates the architecture of a simple DCS.

5.2.1 Automation hierarchy

Automation can be divided into three main hierarchy levels: production management, process control and optimization, and basic automation. As shown in Figure 5.2, the levels have different response times. Production control is used to calculate how to most economically operate a process. It controls the process according to demand and operates according to the production plan. Using production control, the production plan determines how production will be carried out when demand is known. Production planning includes resources such as machines, raw material and labor. Process control and optimization keep the process at the planned optimal operation or adjust the operation to the desired level. Basic automation is responsible for the operations that control the process. (Visala and Halme 2020, pp. 13-14)

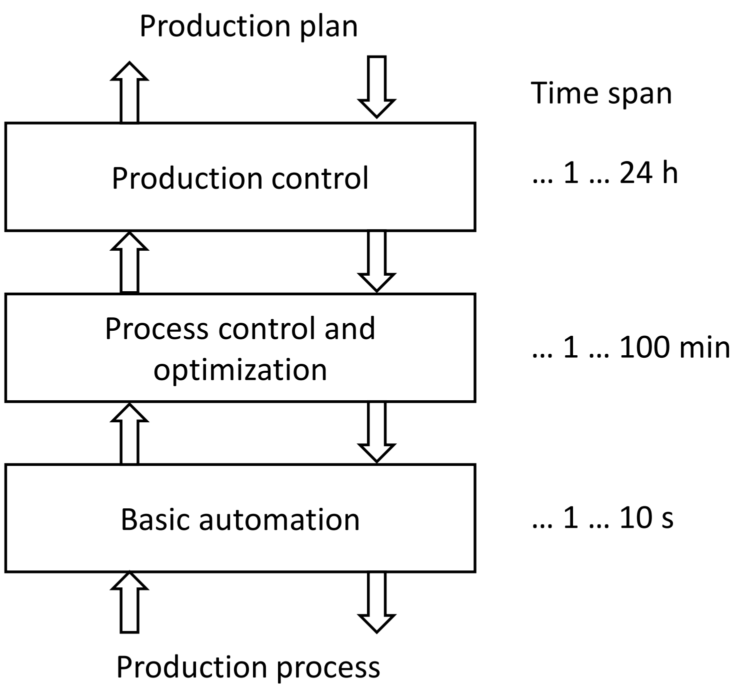

Figure 5.2. *Automation hierarchy (Visala and Halme 2020, pp. 13)*

A typical automation system can be divided into three main operational levels: operation level (control room), control level (cross-connection level) and field instrumentation (field). The classification is based on the purpose of the devices. The main levels are introduced in Figure 5.3. (Opetushallitus 2020).

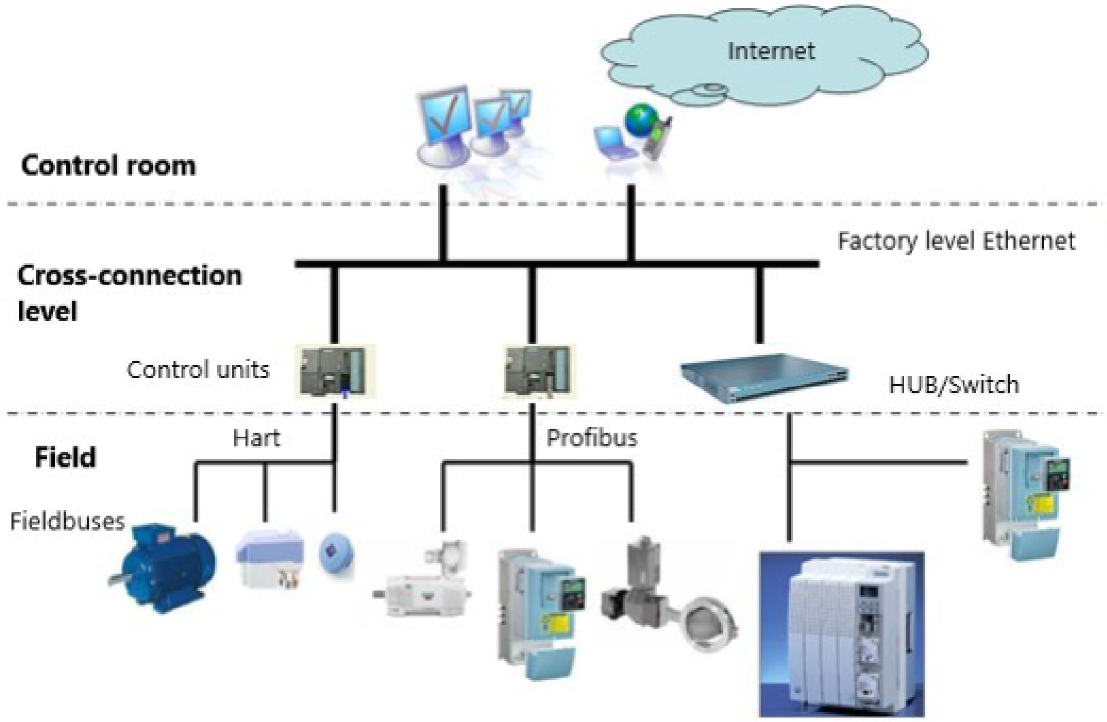

Figure 5.3. *Operational levels in automation systems (Opetushallitus 2020).*

Field instrumentation is the lowest level in the device operational hierarchy. At the field instrumentation level are actuators, sensors, measuring instruments, transmitters and individual control units (Opetushallitus 2020). Sensors and other instruments continuously measure the process and send data to the control units, which calculate the control actions and send them to the actuators.

The control level is in the middle of the operational level hierarchy. At the control level are control units, controllers and logic units for the actuators (Opetushallitus 2020).

The operation level is the highest in the operational hierarchy. At the operation level are graphic displays, controlling terminals and alarm devices. If the system is connected to the local network or internet, it takes place at the operation level. (Opetushallitus 2020) From this level, the processes can be monitored and controlled. If the automation system is connected to the internet, cybersecurity must be considered. More information about cybersecurity is discussed in Chapter 5.3.

5.3 Cyber security

Cybersecurity is essential in automation today. The development of automation systems to take advantage of IT technologies exposes systems to new threats. Many processes are connected to the internet and can be controlled from a distance. It is challenging to protect an automation system from these threats when its life cycle is 15–20 years and the life cycle of IT equipment is only 3–5 years. IT equipment needs to be kept up to date at all times to achieve the necessary protection. If the IT equipment is upgraded, testing and planning are required to minimize interruption in production and to maintain the process reliability. Up-to-date systems, good firewalls and the operators' common sense are all good ways to protect against attacks.

According to Radvanovsky and Brodsky (2016, p. 2), several factors need to be considered for control system security. If there are known vulnerabilities, these risks can be minimized by adopting standardized technology. Risks can include exposing a control system to an unsecured network, implementing constraints of security technologies on control systems, connecting insecure remote devices to the control system and public technical information about the control system. Attackers may try to disrupt the operations in the control system by delaying or blocking the information flow, making unauthorized changes to the PLC, remote terminal unit (RTU) or DCS controllers, modifying software or sending false information to the system to disguise an attack or physical assault on the control modules. These physical attacks can be made to remotely operated processes with no people on site, and an attacker can attack from within the system. (Radvanovsky and Brodsky 2016, pp. 2-5)

5.4 Automation in biogas upgrading

In biogas upgrading, energy efficiency and product quality can be improved by monitoring and controlling the process. The upgrading process can be easily disturbed, and a small error in the process can cause deterioration of product quality as well as environmental impacts. By using real-time control, disruptions can be corrected before they cause quality problems to the process. It is essential to monitor and control the flow, temperature, pressure and pH in the biogas upgrading process.

Biogas upgrading units typically use a PLC, and the upgrading unit is usually integrated with supervisory control and data acquisition (SCADA) software. SCADA is used to monitor the system. The automation system can also be monitored without SCADA, but it would then lack some features (automation 2020). The PLC can be integrated into the DCS, but the integration demands extra components and increases costs. However, the DCS has some features that are hard or impossible to implement in the PLC system. More information about the PLC and DCS can be found in Chapter 5.2.

The dynamics of a process include time-varying control behavior and subsequent response. The control behavior causes changes in the state of the target process according to the laws of physics or chemistry. The automation system needs to manage these dynamic process changes to achieve the desired results. More information about process dynamics can be found in the book by Liu and Gao (2012). Another critical factor in the control of the process is the control system and controllers. Control systems are open or closed, and the controllers used are typically PID controllers. More information about control systems and controllers can be found in the book by Basu and Ahmad (2017).

CH_4 losses are a major concern in biogas upgrading (Miltner et al. 2017). CH_4 is a strong greenhouse gas, and CH_4 losses can be reduced by optimizing and monitoring the upgrading process. During PSA upgrading, CO_2 losses can be decreased by circulating the off-gas back to the inlet. Circulation control is critical because overflow can cause an error in the upgrading process. These errors cause methane losses, and the quality of biomethane can decrease. (Santos et al. 2013)

In physical absorption, the control of solvent flow, temperature and pressure are essential. The control strategy differs between unit manufacturers, but in some units, the water flow depends on the CO_2 content of the biomethane. According to Nie et al. (2013), the optimal gas-to-water ratio is nine. Control of water flow is essential to achieve the optimal degree of upgrading and energy consumption. Pressure and temperature are used to restore the circulating solvent. If conditions in the desorption column are not right, the solubility of the solvent is reduced. More information about the physical absorption process can be found in Chapter 3.1. (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a; Khan et al. 2017)

In chemical absorption, the control of the temperature is essential. The amine solution is regenerated in the stripper column at its boiling point. If the temperature is not correct, the solution will not be regenerated correctly, and the operation of the upgrading units will suffer. It is essential that the temperature is precise and that heating instruments respond quickly. It is also essential to control pressure and flow correctly. More information about the chemical absorption process can be found in Chapter 3.2. (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a; Khan et al. 2017)

PSA is the most commonly used physical absorption upgrading technology. The upgrading is based on pressure changes in the process. The accurate timing of the pressurizing and release of pressure and gases is essential to the correct process operation. PSA is the most sensitive upgrading technology. If the process control does not operate as it should, the quality of the biomethane decreases and CH_4 slip increases. Temperature swing adsorption and electrical swing adsorption are adsorption technologies, but they are not commonly used in biogas upgrading. However, both are sensitive processes in which control of process parameters is essential. The most important parameter for these adsorption technologies is temperature. (Augelletti et al. 2017) In temperature swing adsorption, the problem is the slow response of the heating and cooling instruments. (Vogtenhuber et al. 2017) Automation should respond quickly, and an estimation of the behavior of the heating and cooling instruments is essential. Chapter 3.3 presents more information about the physical adsorption process.

The control of membrane separation technology is not as sensitive as other upgrading technologies because no solvent or material needs to be regenerated. Although biogas needs to be pressurized before it enters the membranes, the operating principles of membrane separation are easier to manage than other technologies. Membranes are especially sensitive to impurities, so the biogas that enters the membranes needs to be purified and monitored to prevent unnecessary contamination. Chapter 3.4 provides more information about membrane separation. (Angelidaki et al. 2018; Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a)

Cryogenic separation is based on the different condensing points of substances. Temperature and pressure controls are essential to achieve efficient separation because the boiling point of the substances depends on temperature and pressure. More information about membrane separation can be found in Chapter 3.5. (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a; Sun et al. 2015)

All upgrading technologies have specific management principles, and some are more sensitive than others. However, all the technologies require active control for correct operation. PSA is the most critical upgrading technology to control because even a small imbalance in the process can cause quality problems and higher CH_4 loss. As discussed earlier, inaccurate control causes quality problems in biomethane and higher CH_4 losses.

All technologies, excluding cryogenic separation, use recirculation to reduce CH_4 losses. Recirculation requires reliable CH_4 and CO_2 sensors to achieve the best balance between CH_4 losses and energy consumption.

Because correct operation of the control system is essential, automation creates value for the customer. But automation can also create value in other ways with system add-on features that are usually software-based.

6 MATERIALS AND METHODS

The objectives of this thesis are to find automation solutions for the biogas upgrading process and determine solutions that create value for the customer. Interviews, data analysis and a literature review were the research methods used. This chapter presents how the research was performed, how the interviews were executed and the background of the interviewees.

6.1 Interviews

The results of the interviews will be discussed on a general level. Specifics of location and identity will not be disclosed to protect the interviewees and their companies. The interviewees were selected from various backgrounds to obtain a comprehensive vision of the opinions related to biogas upgrading technologies and automation needs. The interviewees were selected from among contacts of the control group and the researcher. The interviewees were contacted directly via email and asked for an interview. The interview lasted 1–2 hours and was executed via phone, Microsoft Teams and Zoom due to the COVID-19 pandemic.

Thirteen thematic interviews were conducted for the research. All the interviewees were from Europe, and they had connections to biogas production. The interviewees fell into roughly three categories. Seven of the interviewees worked for a company that produces biogas, two worked for a company that sells or constructs biogas plants and four were experts in the field. Table 6.1 introduces the upgrading technologies used by the interviewees.

The topics of the interviews can be found in Attachment A. With interviewees representing companies that either operate or sell biogas plants, the interview concentrated on the interviewee's own experience. With interviewees considered experts, the interviews concentrated on the big picture of biogas upgrading, the future outlook and their own experience. At the start of each interview, the interviewee's knowledge of the field was

Table 6.1. *Biogas upgrading technologies in interviews.*

Category	Technology
Biogas plant	PSA
Biogas plant	PSA
Biogas plant	Water scrubbing
Biogas plant	Amine scrubbing
Biogas plant	Water scrubbing and membrane separation
Biogas plant	Water scrubbing and membrane separation
Biogas plant	Planned to invest
Retailer	PSA and membrane separation
Retailer	PSA and membrane separation
Expert	-
Expert	-
Expert	-
Expert	-

determined, along with background information on their company and use of upgrading technology.

After this, the direction of the interview depended on the interviewee's knowledge of the technologies and use of those technologies by the company. The second part included questions about automation, a discussion of any problems that have been encountered and how the interviewee sees the future of biomethane. The last part included a discussion of how automation can bring added value to biogas upgrading and to the future of biomethane.

Six of the interviewees worked in a company that produces biomethane via biogas upgrading, and one interviewee represented a company that plans to invest in biogas upgrading. These companies use PSA, membrane, water scrubbing or amine scrubbing technologies to produce biomethane. Two represented retail companies that sell PSA and membrane biogas upgrading technologies. The experts represented various backgrounds from automation, academic research and sensor technology.

6.2 Data analysis

Data was analyzed from three European biogas upgrading plants that use water scrubbing technology. The rated capacity of the plants was 50 GWh/a and 30 GWh/a. All the plants use water scrubbers from the same manufacturer, but the plants were built at different times and used different raw material to produce biogas. The plant service managers were interviewed. For the purpose of this study, the plants are named A, B and C. The automation system used for the data analysis was Valmet DNA.

The main goal of the data analysis was to examine the most common problems and the reasons behind them. The analysis studied the unplanned shutdown times of the plants and the alarms examined before the shutdown. By reviewing the most common alarms, it was possible to examine the correlations between the alarms. The correlations showed what other alarms occurred during the chosen period, the number of other alarms and the rate at which they correlated. The correlation gave a good general view of how different alarms correlate with each other.

Due to the COVID-19 pandemic, it was not possible to visit the plants being examined. The lack of a physical view of the plants and lack of communication with the operators made the research harder to implement and results harder to obtain.

7 RESULTS AND DISCUSSION

7.1 Results of the interviews

The interviews focused on problems that have occurred in biogas upgrading plants and how automation can create value for the customer. Chapter 6.1 presents more information about the interviewees and the implementation method.

7.1.1 Biogas upgrading technologies

Biogas upgrading using water scrubbing technology is the most common upgrading technology used globally. As confirmed in the interviews, water scrubbing technology was also the technology most often used. The advantages and disadvantages of the various technologies as discussed in the interviews are presented in this chapter.

Water scrubber

Water scrubbing was praised for its low operating costs, consistent biomethane quality and closed-system design. Several problems were mentioned. CO_2 utilization is difficult because the off-gas is too humid and mixes too much with air. The system takes more space than other upgrading technologies, and the quality of the biomethane and methane slip is not as good as in some other upgrading technologies. Foaming and bacteria growth can cause problems, and expandability is hard. The question of operation in arctic conditions came up in the interviews. Interviewees believe that the water scrubber units could operate properly in arctic conditions but were uncertain if some of the field devices operate correctly.

Pressure swing adsorption

PSA technology was claimed to be the most inexpensive, the safest and the most convenient in small scale. Interviewees appreciated that it is a dry process and can be shipped and installed in containers. The disadvantages of PSA technology is its high electricity consumption, off-gas CO_2 utilization and slow start-up, especially in colder conditions. One of the main problems PSA have is that it requires lots of adjusting to operate correctly. The automation system in the upgrading units needs to be adjusted correctly, and the system needs to be accurate. Biomethane quality and methane slip can cause problems if the system is not adjusted correctly.

PSA technology was thought to be the most inexpensive, safest and most convenient for small-scale operations. Interviewees appreciated that it is a dry process and can be shipped and installed in containers. The disadvantages of PSA technology are its high electricity consumption, poor off-gas CO_2 utilization and slow startup, especially in colder conditions. One of the biggest problems PSA has is that it requires many adjustments to operate correctly. The automation system in the upgrading units needs to be adjusted correctly, and the system needs to be accurate. The more adjustments needed, the more room for operational error. Biomethane quality and methane slip can cause problems if the system is not adjusted correctly.

Membrane

The advantages of membranes were expandability, reliability, low energy consumption, quality of the off-gas and that it is a dry process. The system is usually oversized, so it can be easily updated to higher capacities by adding more membranes. The system usually uses membrane packages in two stages. This allows the biogas to be controlled by passing through one membrane package, while the other package serves as a backup. Therefore, the system does not need to be shut down if one of the membranes fails. There were references to CO_2 utilization by a biogas upgrading plant where the off-gas was blown directly into a greenhouse. To achieve cost-effective CO_2 utilization with the membranes, the greenhouse needs to be close to the upgrading plant so that the off-gas can be transported via pipes. The utilization of CO_2 is possible with other upgrading technologies, but no other reference was made to this during the interviews. Even 80% of the waste thermal energy in upgrading can be utilized to heat the process water for anaerobic digestion. Thermal energy is recovered using heat pumps. The utilization of thermal energy from upgrading can decrease operating costs and improve efficiency.

One disadvantage of membranes is that biogas needs to be pressurized before entering the membranes. Other disadvantages are that biogas needs to be free from impurities to prevent contamination of membranes and that membranes are expensive, which increases the capital costs of the system.

Amine scrubber

According to interviewees, amine scrubbing advantages included a good quality of biomethane, low methane slip and good resistance to impurities. Even though the system can treat impurities, the off-gas needs to be purified due to odors. Heat energy from the upgrading unit can be used to heat process water for anaerobic digestion. The disadvantages of amine scrubbers are higher capital costs and slow start-up time, especially in colder conditions. The interviewees had problems with a heating device, saying it did not respond fast enough, especially in colder conditions. Furthermore, one interviewee plans to change the old heating device to a new one that will respond quicker. The automation must respond quickly to temperature changes. Predictive control could decrease unnecessary system shutdowns. Additionally, amine scrubbing is suitable only for bigger plants, and process temperatures need to be very accurate for the scrubbers to operate correctly. It is critical to control the temperatures correctly in amine scrubbing because any incorrect temperature can cause the system to shut down and will decrease the quality of biomethane. Chapter 5.4 gives more information about the amine scrubber control principles.

There was disagreement among the interviewees about the capital costs and chemical legislation. The interviewees who used amine scrubbing said that there had been no extra costs or extra work required by chemical legislation. Although it appeared that current chemical legislation is not well communicated, it might negatively affect investment decisions.

Considerations about different upgrading technologies

Active carbon filters were one of the main topics discussed in the interviews. These are filters used to purify biogas from impurities such as H_2S. An active carbon filter needs specific humidity and oxygen content to operate correctly. According to the interviewees, the oxygen content needs to be at least 0.5% to prevent filter deterioration. Low humidity in biogas can cause problems, especially in cold conditions, when air humidity is especially low. Because these filters are expensive, achieving the optimal parameters for the filters is essential.

According to the interviewees, the capital costs of biogas upgrading units must be affordable. Biogas upgrading is not cost effective for small plants. Similarly, compression and liquefaction of biomethane in small plants is unprofitable. It is profitable for a small plant to produce biogas by digestion and then use the biogas in combined heat and power

(CHP) gas engines to generate electricity and heat.

According to the interviews, often biomass pretreatment and feeding equipment are more important for the correct operation of the plant than the upgrading system. The inexperience of new companies has caused uncertainty and difficulties, leading to unfair price competition, and problems during construction and startup. Some suppliers sell the plant equipment to customers but do not supervise the construction work and startup. As a result, the plants have not operated as promised, and features of the system have been left uncompleted. According to some of the interviewees, this has caused considerable uncertainty about biogas upgrading.

7.1.2 Automation in interviews

Biogas upgrading unit automation is usually implemented with a PLC, and as a result, the automation system often lacks essential features. This chapter discusses the problems that interviewees have faced with their automation system and their suggestions for improvements.

Table 7.1. *Automation systems, safety automation and cybersecurity devices in the interviewees' plants. The columns are not related to each other.*

Automation system	Safety automation	Cyber security
Simatic S7	Siemens S7-F	Telia Inmix
Simatic S5	ABB pluto	Tosibox
Valmet DNA	-	-

Most of the upgrading units use Siemens automation system. One interviewee said that the only automation system provider worth considering for biogas plants is Siemens. Table 7.1 introduces the automation systems, safety automation and cybersecurity devices used at the interviewees' plants. Many of the interviewees were not aware of the specific model of their automation system.

Problems that have occurred

Problems that have occurred in biogas upgrading was one of the main discussion topics during the interviews. It appeared that biogas upgrading plants have plenty of problems that interrupt production.

Faulty or failing physical equipment caused most of the problems. There have also been problems with clogged valves, leaking pressure relief valves, choked filters, active carbon filter failures, leaking seals as well as heating and cooling equipment with slow response times. In some plants, automation system cards have broken, and mice have gnawed wires. In many plants, operators have been uncertain of the durability of the field devices, especially in arctic conditions. Some interviewees have had problems with poorly marked field cables.

Some plants have experienced problems with biomethane quality and have found the stated capacity does not correspond to reality. Measuring instruments have been inaccurate, and in some cases, more sensors were desirable. One plant had problems with nitrogen gases leaking into the biogas from a faulty pump. There were no sensors in the system to measure the nitrogen content, so troubleshooting was difficult. The high nitrogen content lowered the quality of biomethane, causing unnecessary shutdowns. One CO_2 sensor was inaccurate, which caused issues because water scrubber operations depend on the CO_2 content of the biomethane. The resulting delay in the measurement of CO_2 led to inaccurate readings. All these issues caused quality problems. The companies using this control system wished to have more predictivity over the CO_2 content in biomethane. Other chemicals that have caused problems in upgrading are siloxanes and limonenes because they are difficult to measure and filter.

Some interviewees have had problems with black-box automation. Black-box automation means secure automation that cannot be changed without authorization. Automation in a black box can be protected with a password, so only authorized persons are allowed to make changes in it. Troubleshooting has been hard due to black-box automation, and some interviewees have not been able to correct the faults, because they do not have access to the protected logics. Some of the interviewees hoped the automation system could be as open as possible to prevent the previously mentioned problems.

Other things that came up in the interviews were inferior touchscreen operation and SMS alerts. The touchscreen can cause problems because service personnel usually use protective clothing, including gloves. If their hands are dirty, this causes a problem when registering input on the touchscreen. One interviewee suggested that some manufacturers make better reporting software than others.

Fault handling and alarms

Backup systems in automation are not often used in biogas plants due to higher capital costs. During the interviews, it seemed that only critical measurements are doubled in some cases. The lack of a backup system can cause problems if an automation card or control unit fails. In some plants, sensor failures can be bypassed by manually supplying measurements to the automation system. In those situations, it is essential to ensure that the process works properly with other measurements. Some interviewees wished that their field devices could be more reliable and durable. Inadequate field devices have caused problems, especially in arctic conditions where they have given failure signals that have caused shutdowns, even though the process has not been affected.

Some interviewees highlighted the importance of alarms. Many hoped that the alarms could be better prioritized. Several interviewees use remote control rooms and would like only critical alerts would be reported there. Some plants have performed prioritization after installation, resulting in extra work. Interviewees from some of the plants prefer that critical alarms would not cause an immediate shutdown. Instead, the automation system should wait until there is a change in the process before shutting down. Any alarm delay can prevent unnecessary shutdowns if a field device issues an unnecessary error. Often, alarms are delayed too long, or the alarm may not be appropriately displayed. One interviewee would like to see alarms appearing on all monitors in the control room so that operators could react more quickly.

Need of automation

The interviewees would like to see automation providing consistent quality and reliability. As discussed earlier, black-box automation has caused problems, so interviewees hoped the automation system could be as open as possible. There were contradictions in their opinions about integrating the processes within one automation system. Some interviewees said that integrating all processes under one automation system is unnecessary because it leads to increased investment costs. However, others would be willing to invest in the integration.

Field device alternation was carried out in some plants with duplicated field devices. Duplicated field devices help to predict the service schedule when both devices have the same operation time. Reporting came up in the interviews quite often. Interviewees would like to see an easy and comprehensive reporting system.

Measurement data

The interviews revealed inconsistencies about the need for measurement data. Some of the interviewees hoped for more measuring instruments. Others said nothing else was needed for reporting to the public authorities and to ensure proper process operation. The additional measurements desired were biogas CH_4 content before upgrading, humidity and dew point after upgrading, electricity consumption, portable measuring instruments, continuous oxygen measuring before upgrading, bacteria growth in water scrubbers, chemical composition and digestion acidity.

Off gas and CO_2 utilization

Methane slip was one of the main subjects discussed with the interviewees. Most of the interviewees were not worried about CH_4 slip if the plant operated correctly, but all of them were uncertain about future restrictions. The interviewees believe that restrictions will come soon, but none of them have prepared for it. Some of the interviewees were afraid that small biogas plants would have to close if the equipment capital costs are too high. They are aware that some European counties have restrictions on CH_4 slip.

Some interviewees have examined the possibility of utilizing CO_2, but almost everyone said that it is not economically viable. The main problems are the low price of CO_2 and the price of the equipment needed for CO_2 utilization. As discussed earlier in chapter 7.1.1, the off-gas can be blown directly into a greenhouse, which is an economically viable option. CO_2 utilization in water scrubbers or PSA is not possible without extra equipment to separate the CO_2 from air and humidity. Some plants have examined the option of combining the methanation process with biogas production by producing electricity with solar panels. However, the capital costs are too high for this option to be economically viable. More information about the methanation process has been discussed in chapter 2.2.1.

7.1.3 Future of biomethane

Future

Interviewees feel that biomethane has a bright future, but some challenges need to be overcome. One of the main topics the interviewees brought up was using biomethane as fuel for heavy traffic. Some of the interviewees see that the only viable option to reduce the carbon footprint of heavy traffic is to use biomethane as fuel. They think battery technology for heavy traffic is not a viable option in the near future. Some interviewees believe that the size of biogas plants could increase in the future, making CO_2 utilization economically viable. Several mentioned that biogas plays a significant role in achieving Europe's emission targets.

Some of the interviewees said that CH_4 slip is a big problem. Most of the interviewees were not prepared for stricter regulations, and they mentioned a considerable amount of doubt about CH_4 slip. Some respondents considered hydrogen as a challenge but think it will not compete with biomethane in the near future. Natural gas leaks have deteriorated the image of biomethane. Especially in the US, there have been problems with natural gas grid leaks. In Scandinavia, taxation causes problems, and plants are afraid that taxation will reduce the number of gasoline cars. One interviewee said that biomethane in Finland has the same problems wind power had ten years ago.

Value creation

Traceability would help track the origin of bad gas quality if the sensors give a faulty reading and the fault is discovered afterward. The circular economy and local energy are some of the main selling points of biogas and biomethane.

A few interviewees hoped that automation systems for different process areas could be combined. The various process areas mentioned were feeding equipment, anaerobic digestion, biogas upgrading and gas grid injection, fueling station or gas container loading. However, some respondents said that it is unnecessary to combine automation systems if the process already works well enough, because integration would just cause extra costs. It was emphasized many times that the automation system needs to be cheap and functional.

As discussed earlier in Chapter 7.1.2, reporting is essential in upgrading plants, and many have had problems with it. Some interviewees hoped for reporting improvements. Some wished that reports would go directly to the cloud and could be automatically sent to them, for example, by email.

An open automation system and better equipment automation were widely desired. Process automation graphic displays have worked well according to the respondents, but some wished that the screen could be more uncluttered, so that even an inexperienced person would be able to understand it. They hoped the graphic displays could contain only critical information and that all other information would be hidden.

7.2 Data analysis

Data analysis focused on the most common alarms and reasons for them. The alarms examined were only from biogas upgrading units. More information about the plants and data analysis implementation is discussed in Chapter 6.2.

7.2.1 The most common problems and correlations

Plant A

Figure 7.1 presents the ten most common alarms that caused shutdowns in plant A.

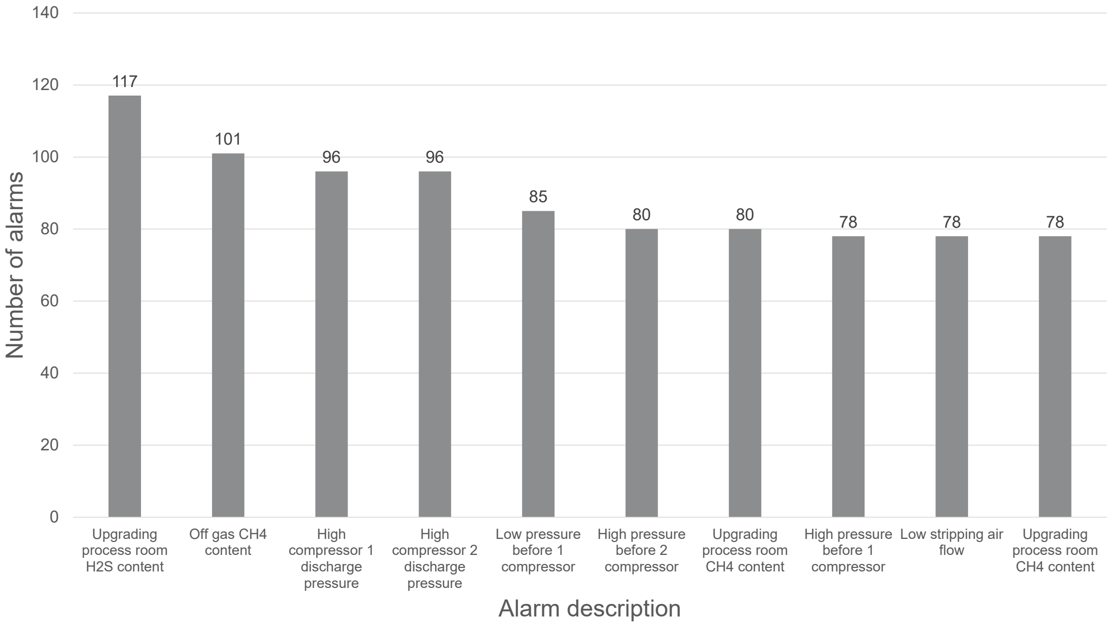

Figure 7.1. *Most common critical alarms in plant A*

All of the alarms shown in Figure 7.1 often correlated with alarms caused by the safety automation system. In most cases, the safety system instrument alarm seems to have caused the alarms. The plant's service manager mentioned this problem had occurred sometimes when the current of the analog field device or sensor dropped under 4 mA. A low electric current in the analog field devices or sensor is only one possible reason for the alarms. The field voltage power supply was changed after the period examined and has minimized the shutdowns caused by the safety automation. Apparently, the safety automation limits are too strict, so even a small error in the process causes a shutdown. Furthermore, it was evident from alarms before the shutdowns that the safety automation gave off many different types of alarms. This indicates that some error in the process triggers many safety automation alarms at the same time. The safety automation in this case is typical for black-box automation, which means the plant employees have had problems determining the reason for the alarms. More information about the problem and improvement proposals can be found in Chapter 7.5.1.

Plant B

Ten of the most common alarms that caused shutdowns in plant B are shown in Figure 7.2.

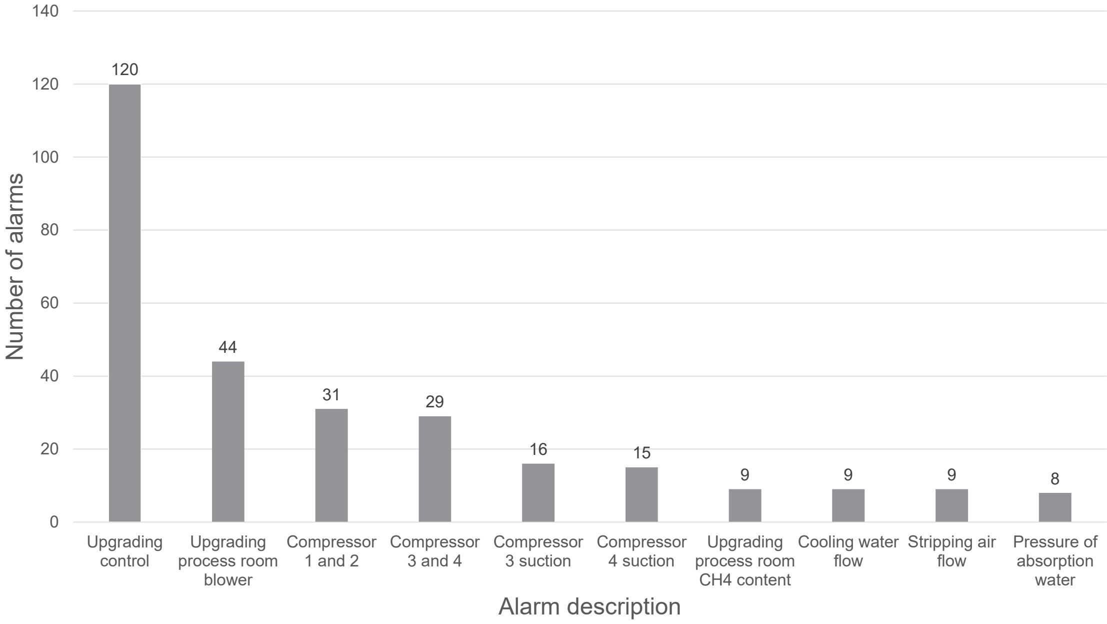

Figure 7.2. *Most common critical alarms in plant B.*

The **Upgrading control** alarm was the most common, going off 120 times during the period examined. This general alarm shuts down the upgrading unit. The problems stem from disturbances in the raw biogas storage. The plant's service manager noted there were problems with the gas holder. The level of the gas holder had increased while the capacity of the upgrading unit decreased. The service manager said in the interview that the problem had been fixed.

The **Upgrading process control room blower** alarm went off if the capacity of the upgrading unit dropped under 50%. The event causing the alarm was an operating fault.

Compressor 1 and 2 and **compressor 3 and 4** alarms were caused for the same reason. The alarms occurred when the compressor units were not ready to operate. The alarms also correlated with the safety automation's alarms, indicating that in some cases the safety automation has caused the problem.

Compressor 3 suction, **compressor 4 suction**, **upgrading process room CH_4 content**, **cooling water flow**, **stripping air flow** and **pressure of absorption water** alarms were caused by the safety automation alarm. The reason may be the same as in plant A.

Plant C

Plant C did not have any critical alerts from the upgrading unit during the period examined that caused immediate shutdowns.

7.2.2 Availability

The data analysis also examined the availability of biogas upgrading plants. Figure 7.3 shows one plant's biomethane production in relation to nominal capacity. The availability rate means the percentage of time when the upgrading unit is available and ready to be used. The utilization rate means the percentage of time when the plant is operated. As we can see from the figure, the biomethane production was not steady. Even though it was unstable, the availability rate for the plant was around 99% during the period examined. The unstable production rate was caused by other parts of the plant. Plant A's availability rate is shown in Figure 7.5.

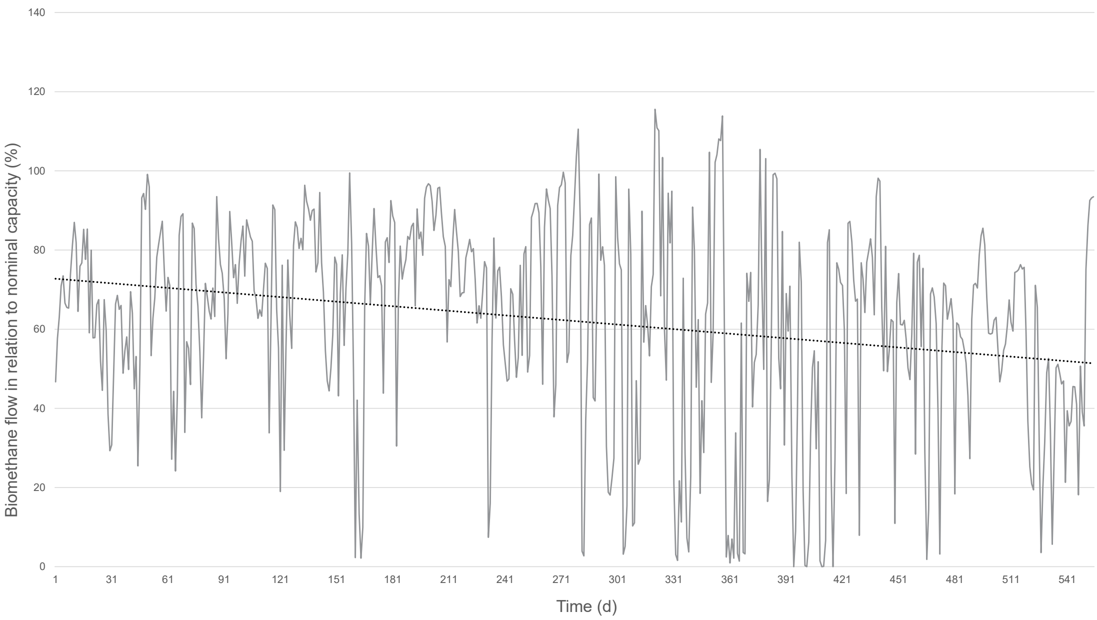

Figure 7.3. *Plant A's daily average biomethane production capacity.*

The daily average biomethane production capacity of plant B is shown in Figure 7.4. Even though the graphic indicates that operations at plant B were more stable than at plant A, the availability rate of plant B was worse during the period examined – 96% at plant B and 99% at plant A.

However, even though the availability rate of plant A was 99% during the period examined, the average utilization rate was around 78%. This low utilization rate was due to other factors such as not enough raw biogas to operate the plant at nominal capacity or

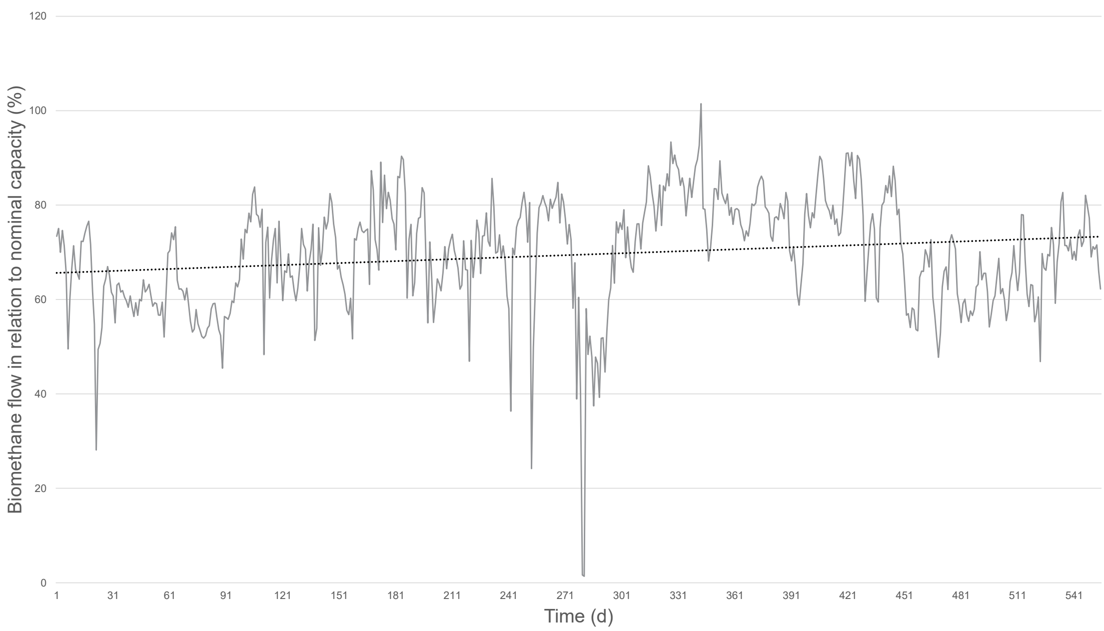

Figure 7.4. *Plant B's daily average biomethane production capacity.*

problems in other parts of the plant. Troubles with the safety automation alarm was one of the main problems in plant A.

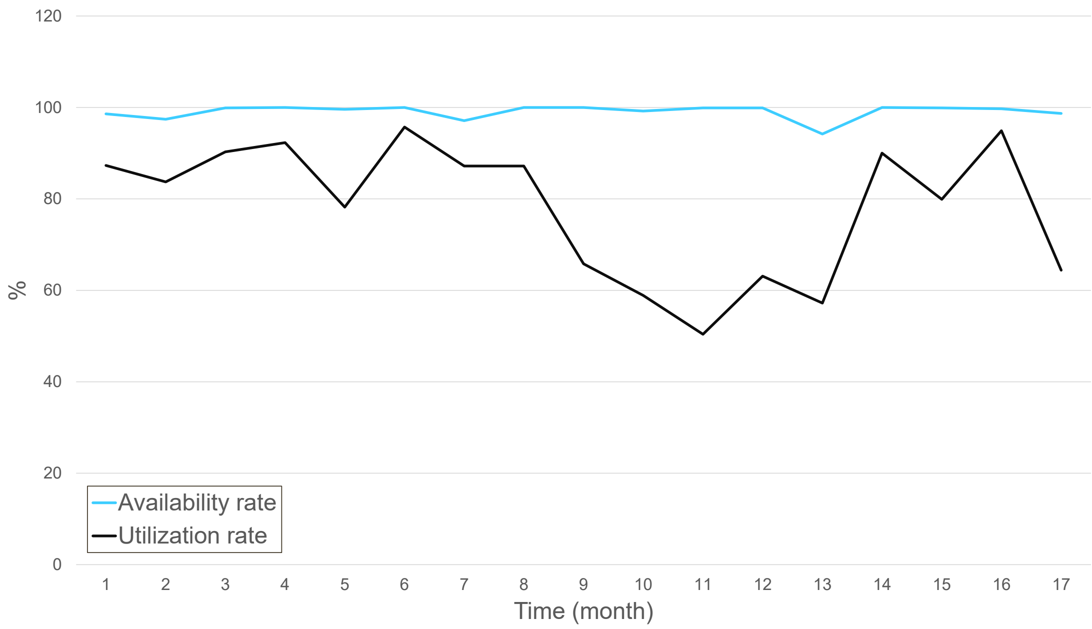

Figure 7.5. *Plant A's availability and utilization rates.*

The availability and utilization rates of the plants examined are shown in Table 7.2. The rates have been calculated from monthly averages for the period examined. In plants B and C, two months have been left out of the calculations because the reports were missing parameters and were therefore not considered reliable.

Table 7.2. *Availability and utilization rates of plants calculated from monthly average*

Plant	Availability rate	Utilization rate
A	99.1%	78.0%
B	97.3%	97.2%
C	99.6%	97.5%

Plant A had the most problems and its utilization rate was the worst. As discussed in Chapter 7.2.1, plant A suffered from safety automation problems and increased hydrogen content. A gas that contains hydrogen must not enter the upgrading unit. Plant B also suffered from safety automation problems but to a lesser degree. Plant C had the fewest problems and the best utilization rate of all the plants examined.

Overall, the availability rate of the biogas upgrading units has been quite good even though the utilization of each unit could be better. The most common problems in the upgrading units of plants A and B are discussed in Chapter 7.2.1. Safety automation has caused problems that should be solved to improve each plant's utilization rate. Plant A's service manager said that they had a problem with high hydrogen content. This caused unnecessary shutdowns. The reason for the high hydrogen content is probably unbalanced anaerobic digestion. According to Kymäläinen and Pakarinen (2015, p. 78), the reason for high hydrogen content is when the methanogenesis phase does not use enough hydrogen. The resulting high hydrogen content reduces the operation of the acidogenesis phase.

7.3 Availability and failure situations

Loss of the availability of a biogas upgrading plant can significantly reduce the plant's profitability. Even a couple of hours of extended plant downtime can cause significant losses to the company. Predictable service and reliable field devices can reduce the downtime of any system. Methods to predict the condition of field devices and measuring instruments are discussed in Chapter 7.5.

Figure 7.6 shows the financial losses resulting from unnecessary shutdowns at a biogas upgrading plants with a capacity of 500 Nm^3/h when the price of biomethane is EUR 1 43/kg (Gasum 2020). Income from biomethane sales are EUR 11,000/day, so reducing unnecessary shutdowns is vital for the company.

From the interviews, it can be seen that the companies want automation systems for their

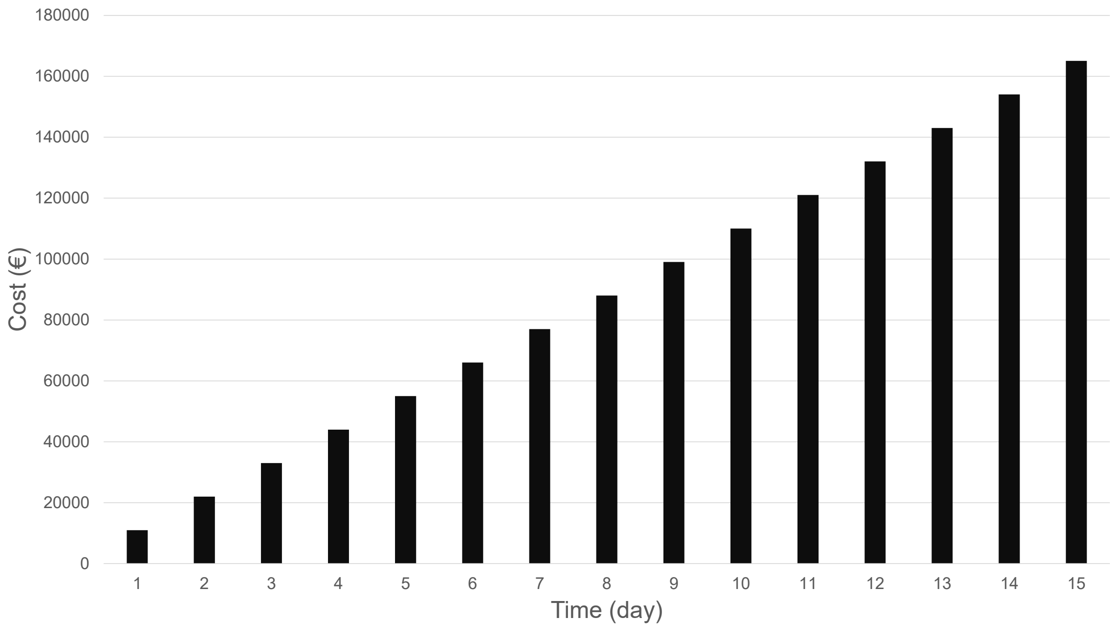

Figure 7.6. *Costs of shutdown.*

biogas upgrading plants to be as cheap as possible. However, when an automation system is implemented at the lowest possible price, it is probably missing features designed to reduce shutdowns. These features are discussed in Chapter 7.5.

Diagnosing the reason for failure can be difficult if alarm systems and trends are hard to use. It is essential to be able to find and repair the fault to avoid additional problems in the future. Useful tools for diagnosing failures are alarms, history modes and trends. In some cases, diagnosing alarms can be useful in failure diagnostics. However, the alarm may indicate the reason for failure, but still not report the primary cause of the failure. The history mode on the graphic display can be used to examine what has happened in the process and can specify the primary cause of failure if the alarms do not give enough information. Trends can be used in the same way as the history mode but can more accurately determine what has happened in the process. More information about diagnostics is presented in Chapter 7.5. Often the primary cause of failure is difficult to determine. Chapter 7.2.1 discusses just such a failure caused by a safety automation black-box problem.

7.4 Integration of biogas processes

The integration of the processes makes process control easier, which is relevant to customers. It appeared from the interviews, though, that some plants are not interested in integrating the processes because of the increased automation system cost. As the biogas upgrading process is often built after the anaerobic digestion process, some kind of process integration is essential for proper operation. Even though the customer may not want to integrate the processes under one automation system, the processes need to communicate with each other to achieve accurate operations.

The easiest way to get different automation systems to communicate with each other is to branch the measuring instrument's cable to both automation systems. This is cheap and easy way to get measuring data from one process to another but has its limitations. The automation systems still do not communicate with each other. In an error situation, the error does not appear in the other system before changes are made to the process. The automation system cannot anticipate other processes, which can cause problems. Some interfacing methods that allow communication between different automation systems are shown in Figure 7.7. More information about interfaces is discussed in Chapter 5.2.

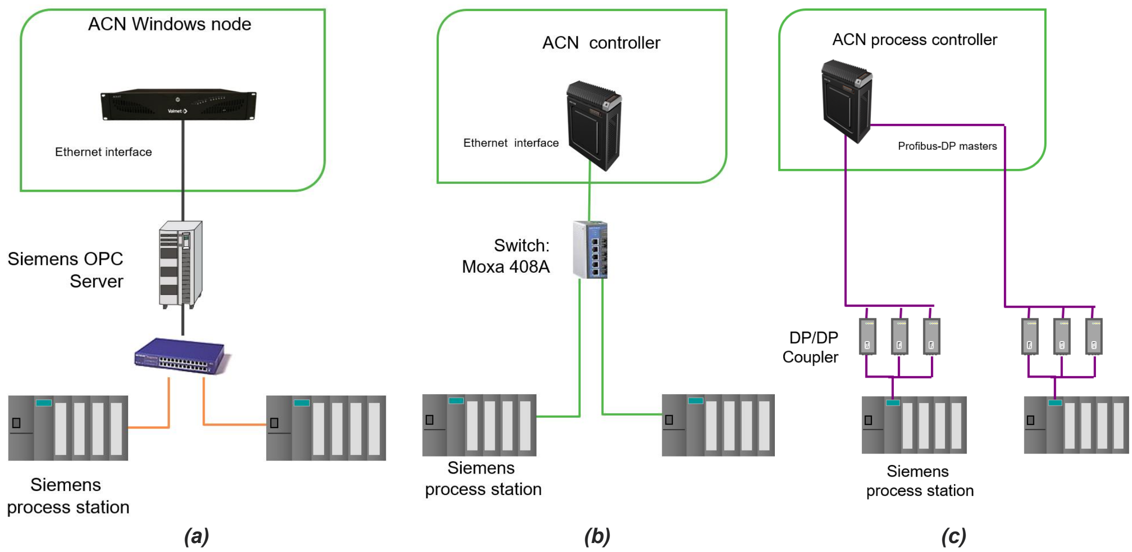

Figure 7.7. *Interface between Valmet DNA and Siemens.*

Optional extras that would be added afterwards to the system and create value for the customer are introduced in chapter 7.5.

Connection under one DCS automation system makes it easier to add on optional extras afterward. Optional extras that can create value for the customer are discussed in Chapter 7.5.

7.5 Value creation with automation

Automation has a big role in value creation. Sometimes customers do not know what to request. Because suppliers have experience in the field, they can help the customer find the best possible solution. The biogas business is quite new, and many customers do not know what they need. They may choose the cheapest solution only to find it is missing some features or the features are poorly implemented. From the interviews, it seems some companies had problems with missing automation system features. If they could make their decision over, they would like to have more features. This chapter collects some of the main features that interviewees felt were missing and introduces some automation system features that can create value for the customer. Interviewees hoped that the automation system would be designed in a user-friendly way and that the automation system provider would have experience in this field. Results of the interviews are presented in Chapter 7.1.2.

The automation of a biogas upgrading unit is usually implemented by the manufacturer of the upgrading unit using a PLC. The PLC is then integrated with the plant's automation system. Valmet DNA is a DCS-based automation system, which can be used to control the whole plant. More information on automation can be found in Chapter 5 and on the integration of the processes in Chapter 7.4. Value creation often comes from features that can be added to the automation system. The upgradability and features of the automation system add value for the customer. Service and spare parts are also essential for a plant's life cycle, as it is vital to secure operations in case of component failure.

7.5.1 Black box

During the purchasing phase, customers are often not aware of all the features included in an automation system. Black-box automation in particular causes many problems later. When problems appear, the reason for failure must be determined and fixed. As presented in Chapter 6.1, the interviewees have had problems with black-box automation and have had to wait until the warranty is over to be able to change the process parameters. The data analysis shows that password-protected safety automation may have caused many shutdowns. The reason for the shutdowns is not entirely certain, but it seems that the limits of safety automation are too strict. These limits cannot be examined, because they are part of the black box, which is protected by passwords. It is essential to protect safety automation so that it cannot be changed. Changes in safety automation cause a safety risk if they are performed by someone unauthorized to make changes. So, the customer and automation system provider must communicate with each other to find the fault as fast as possible.

Together, they must agree on which part of the automation system presents a black box for their operations and how to change this black-box automation if needed. In some cases, the biogas upgrading plant provider went bankrupt or is out of business. This has left the customer unable to make changes to the black-box automation because it is password protected. It is important to understand that startup companies especially are at a higher risk of bankruptcy and they may not have much experience from this field. A lack of references may also indicate that their technology has not yet been established, and unsolved problems may still exist.

7.5.2 Measuring instruments

As data from measuring instruments control the process, the correct operation of the instruments is critical. The process control varies depending on the automation used, but data is still collected from the measuring instruments and used to control the process. Some measurements are easy and inexpensive to implement, but the measurement of certain substances is challenging and expensive. For example, nitrogen (N_2) caused problems in one plant that did not have any measuring instruments that could detect the N_2. Nitrogen measuring instruments are expensive and do not endure continuous exposure to gases. One solution can be to make a measuring point with a N_2 detecting measuring instrument in the system. The gas is connected to the sensor only when the disturbance is suspected to be due to N_2.

Sensor reliability and accuracy are essential. Occasionally, gas measuring instruments need to be calibrated with calibration gases. For the correct process operation, the measuring instruments must operate correctly. Reliable and accurate sensors that do not need calibration gas may be more expensive, but they may pay for themselves in the case of sensor failure. With an accurate sensor, the process operates at the best possible parameters, reducing CH_4 slip and decreasing energy consumption as well as improving the biomethane quality and the overall process efficiency. Some sensors do not need calibration gases but use infrared technology instead. This ensures that the delicate part of the sensor does not come in contact with the gases. Some measuring instruments can measure CH_4, CO_2 and humidity in one unit. In this case, there are fewer service points, as one sensor can measure multiple gases. (Vaisala 2020) Some interviewees hope to get the CH_4 content and humidity measurements before the upgrading process.

Even though customers do not want more than the required measuring instruments for the process, the ease of use afterward is essential. The measuring instrument must be easy to integrate into the automation system. Especially if the CH_4 slip regulations become stricter, companies may have to invest in new measuring instruments and additional equipment to reduce CH_4 slip.

Some of the interviewees wanted measurements to be limited to what is required by the authorities. Their reasoning was that more measuring instruments would increase the capital cost of the plant and the cost of the automation system. However, in many cases, more measuring points can be valuable for the customer. Failure diagnosis can be easier when there is more data available, and the instruments might pay for themselves. More information about failure diagnostics is discussed in Chapter 7.3.

Condition monitoring of pumps and compressors can reduce plant downtime and reduce maintenance costs when service occurs before a failure. The condition of pumps and compressors can be monitored with vibration-based condition monitoring, which can be used on rotating machinery. The condition, runnability and lubrication of diagnostic devices can be monitored with a vibration-based condition monitoring system.

7.5.3 Trends and reporting

The importance of reports was mentioned in the interviews and shown in the data analysis. Reporting is a mandatory part of automation systems because biogas upgrading plants must report their production and greenhouse gases to the authorities. The specific parameters that need to be reported depend on the country. Reporting also helps plants monitor their production.

Reporting to a cloud service enables personnel to view the reports from a distance. Personnel who need the reports are often not located at the plant. The same applies to trend reports and data. Automatically emailing reports to the personnel would help them remember to review them and send them on to the authorities. An automatic sending function could reduce working hours and increase efficiency.

From the interviews, it appeared that current reports and trends are lacking some features and are hard to use. These kinds of problems may not become obvious until transactions have been made and the plant is operating. It is therefore important to demonstrate to the customer how the reporting and trends work. The value that reports and trends create for the customer can be hard to demonstrate and understand if the customer has only had previous experience with poorly implemented reports and trends. The history mode in the graphic displays can be important to the customer for failure diagnostics. More information on this is presented in Chapter 7.3.

7.5.4 Traceability

Traceability of the biomethane produced can be a valuable feature when investigating a faulty batch. Tracing requires reliable biomethane quality control. By tracking a faulty consignment, a company can prevent additional costs and avoid damaging its reputation. Tracing the quality of biomethane could also open more business opportunities if the end user requests tracking and a specific quality report of the shipment. Companies buying biomethane might perceive suppliers who provide tracking as being more desirable and choose them over suppliers who do not. A container gas monitoring system could also be integrated with the tracking to monitor the state of the gas container. A logistics company can monitor the state of the containers and pick up the container when it is full. Monitoring the gas container state can improve efficiency and reduce capital costs. There are references of companies that have invested in overcapacity to always ensure an extra gas container. The reason for wanting overcapacity is to make certain to have enough capacity for the biomethane. Owning an overcapacity of gas containers binds capital that could be better used elsewhere. The price of biomethane may also be higher, if it is determined by energy content and not by weight.

The reputation of companies could also be enhanced if they provide an opportunity for real-time tracking of the process on their web page. Real-time tracking is not suitable for private enterprises but can be valuable for municipal enterprises that produce biomethane from waste or sewage. These companies may not want real-time tracing immediately, but the opportunity may offer value in the future.

7.6 Comparison of upgrading technologies

This chapter compares upgrading technologies based on the literature and interviews. The interviews have been presented in Chapter 66.1. The most common biogas upgrading technologies are discussed in Chapter 3. All technologies have advantages and disadvantages, and some technologies suit a specific application better than others. Table 7.3 shows the parameters of upgrading technologies mentioned in the literature. More information about upgrading technologies is discussed in Chapter 3.

Table 7.3. *Table of biogas upgrading technologies properties (Angelidaki et al. 2018; Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a; Bauer, Persson et al. 2013; Sun et al. 2015).*

Parameter	Water scrubber	Organic physical scrubbing	Amine scrubbing	Pressure swing adsoprtion	Membrane separation	Cryogenic separation
CH_4 (vol %)	> 97	> 96	> 99	96-98	96-98	97-98
CH_4 losses (%)	< 2	2-4	< 0.1	2-4	< 0.6	< 1
Efficiency (%)	92.7-96	90-95.5	88.5-97.7	84.8-93.6	82.4-98	84.9-96.7
CC (€/kWh)	357-731	510-969	264-438	255-831	305-367	394-960
OMC (€/kWh)	0.47-0.94	0.92-1.05	1.15-1.92	0.92-6.5	0.79-5.5	4.8-7.1
Electricity consumption (kWh/Nm^3)	0.3-0.5	0.49-0.67	0.27-0.3	0.3-1	0.25-0.43	0.8-1.54
Capacity (Nm^3/h)	> 5	> 100	> 100	> 5	> 100	> 5
Pre-purification	No	Recommended	Yes	Yes	Recommended	Yes
Removal of O_2 and N_2	No	No	No	Possible	Partial	Yes
Removal of H_2S	Yes	Possible	Contaminant	Possible	Possible	Yes
Operation pressure (bar)	4-10	4-8	atm	3-10	5-8	80-200
Pressure at outlet (bar)	7-10	1.3-7.5	4-5	4-5	4-6	8-10
Separated CO_2 (%)	80-90	-	92-93 + (CH_4 5-6)	> 93	-	98 + (CH_4 0.6)

Amine scrubbing achieves the highest quality of biomethane and the lowest CH_4 slip. Off-gas CO_2 can be utilized without any additional treatment. Conflicting opinions about the capital costs (CC) was apparent during the interviews. (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a) It was mentioned in the interviews that the capital cost of an amine scrubber is 25–30% higher than other technologies. However, the literature states that the capital cost of this technology is lower than for most other upgrading technologies. The reason for this discrepancy may be that amine scrubbing suits higher capacity applications best. The upgrading plants of almost all those interviewed were smaller than 500 Nm^3/h. Figure 7.8 shows the effect of capacity on capital cost. The price in EUR/Nm3/h drops when the capacity of the upgrading plant increases.

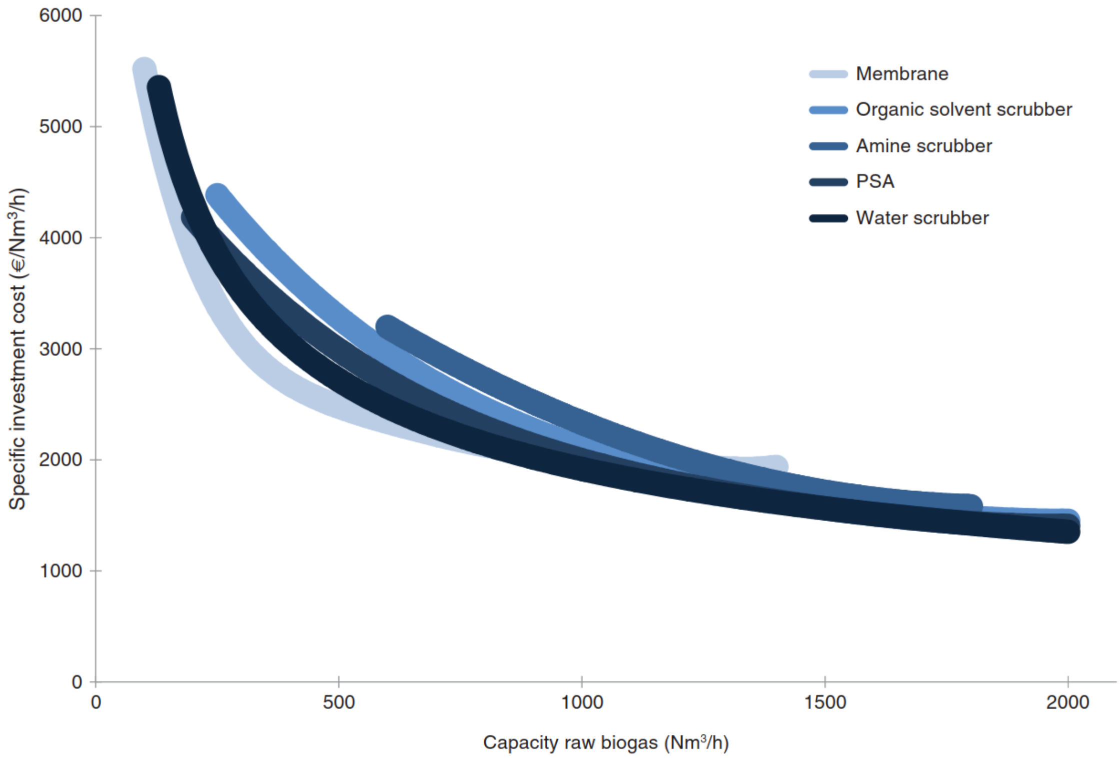

Figure 7.8. *Capital cost dependence on raw biogas capacity with different biogas upgrading technologies (Bauer, Persson et al. 2013)*

As amine scrubbing is the only upgrading technology that operates at atmospheric pressure, it is easier to use its synergies in other applications because the gas does not need to be pressurized. For example, amine scrubbing technology is used in oil refineries and for the carbon capture of flue gases. Operation and maintenance costs (OMC) are high in amine scrubbing due to high thermal energy demand (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a). The thermal energy is used to recover the amine solvent but can be used to heat up the process water, which decreases the entire plant's thermal energy demand. It is essential to keep process temperatures at the right degree, and the system needs a good heat supply to prevent unnecessary shutdowns. (Sun et al. 2015) From the interviews, it seems amine scrubbers can handle H_2S, but the literature states it is a contaminant

Membrane separation can achieve a 96–98% biomethane purity and CH_4 slip less than 0,6%. This technology was especially praised for its reliability and scalability. It is suitable for medium and large plants (Sun et al. 2015). CC and OMC are moderately low, and the system does not use much electricity (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a). The system needs thermal energy, but this energy can also be used to heat the process water. According to one interviewee, 80% of the thermal energy can be recycled in the process water. Off-gas CO_2 utilization is easy, and references show that CO_2 can be blown directly into a greenhouse.

The disadvantages of membrane separation are the high cost of membranes and that they can deteriorate if impurities enter the membranes. Prepurification is essential in membrane upgrading to prevent unnecessary membrane deterioration (Khan et al. 2017). Biogas upgrading using membrane separation is slightly more expensive than PSA, which is the toughest competing technology for membranes according to interviews.

Water scrubbers are the most commonly used upgrading technology (Angelidaki et al. 2018). The operation principle is simple. The purity of biomethane is more than 97%, and CH_4 losses are less than 2%. CC and OMC are moderately low, and the system does not use much electricity (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a). The interviewees appreciated the low operation costs and the even quality of the biomethane produced. Water scrubbers have a high tolerance to impurities and can remove H_2S (Miltner et al. 2017). The prepurification is not as crucial in water scrubbers as it is in other upgrading technologies. (Bauer, Hulteberg et al. 2013)

Biomethane quality and CH_4 losses are higher in water scrubbers than in other technologies, and bacteria growth and foaming can cause problems (Khan et al. 2017). From the interviews, it appeared that off-gas CO_2 utilization is not easy. The off-gas contains moisture which needs to be removed before utilization. The biomethane has a slightly higher pressure than in some other upgrading technologies, which decreases the amount of energy needed to pressurize it if it is converted to liquefied biogas (LBG) or compressed biogas (CBG) (Bauer, Persson et al. 2013).

Organic physical scrubbing technology was not brought up in the interviews. Although it is not an extensively used technology, it has the same characteristics as water scrubbing. The biomethane quality is worse than with a water scrubber, and CH_4 losses are higher. The technology also requires both pretreatment and purification. (Sun et al. 2015) However, some solvents can be used to remove H_2S from the biogas.

PSA can achieve a 96—98% biomethane purity, and CH_4 slip is 2—4% (Sun et al. 2015). PSA upgrading is relatively inexpensive. The technology is the best choice for small plants, according to interviewees. Some said that it is the safest upgrading technology. PSA can be used to remove O_2, N_2 and H_2S.

The adjustment in PSA is critical, and even a small inaccuracy can cause bad quality and higher CH_4 losses.

Still, PSA requires prepurification. Impurities such as siloxanes can contaminate the adsorber materials. PSA requires a lot more electricity that cannot be used for anything else (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a). The utilization of CO_2 is hard because the off-gas mixes with air, decreasing the CO_2 content of the off-gas. The off-gas can contain much more CH_4 than it should if the system is not adjusted correctly. In some PSA plants, the CH_4 slip has been 10—12%, even though suppliers say the losses are lower than 2% (Sun et al. 2015). The adjustment in PSA is critical. Even small inaccuracies can cause bad quality and higher CH_4 losses.

Cryogenic separation technology was not discussed in the interviews. Biomethane quality with this technology is 97–98%, and CH_4 slip is less than 1%. CC and OMC are higher than with other upgrading technologies, and the technology is not widely used. (Baena-Moreno, Rodríguez-Galán, Vega, L. F. Vilches et al. 2019a; Sun et al. 2015) According to Angelidaki et al. (2018), there was only one biogas upgrading plant that used cryogenic separation in 2018. The technology works best if biomethane is converted to LBG. The technology needs prepurification, but it can be used to remove O_2, N_2 and H_2S from the biogas.

All the technologies have their own specific applications and different properties. Amine scrubbing technology is promising, and many large corporations have invested in this technology. The regulations on reducing CH_4 slip and producing a high quality of biomethane force companies to provide cleaner upgrading technologies – and amine will be one of them. Membrane and cryogenic separation seem like viable technologies in biogas upgrading. Biomethane quality and CH_4 slip are not as good in membrane separation as in amine scrubbing, but membrane separation suits other applications better. Amine scrubbing and membrane separation are both fairly well-established technologies. Cryogenic separation is a promising technology if biomethane is converted to LBG. Water scrubbing, organic physical scrubbing and PSA suffer from higher CH_4 slip, and the biomethane quality is lower than in other upgrading technologies. However, they have their own applications and suit small biogas plants well. These technologies are well established and have many references.

7.7 Suppliers of biogas upgrading technologies

This thesis examined the companies providing biogas upgrading technologies and the technologies they supply. These companies were found in the IEA Bioenergy Task 37 report (IEA 2016), the European Biogas Associations report (EBA 2018) and the interviews. The companies' product portfolio and references were examined by reviewing their web pages and reports. The IEA Task 37 report from 2016 and the EBA report were used as the basis to study the companies. Some of the companies mentioned in the reports went bankrupt or were sold to larger companies. A few newer companies that did not appear in the reports were discovered during the interviews. Many companies may not be included, especially in Asia and Africa, but the focus of this research was to examine companies located in Europe and North America. A company is considered to be small if its turnover is less than EUR 10 million and large if its turnover is more than EUR 50 million (Statistics-Finland 2020).

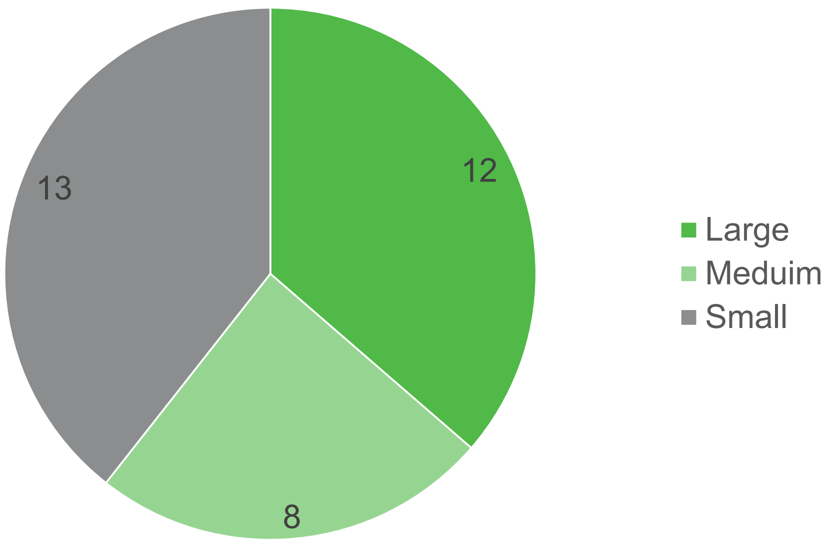

Figure 7.9. *The sizes of companies that manufacture biogas upgrading units.*

Figure 7.9 shows the sizes of the companies whose economic indicators were found in public sources. As discussed in Chapter 7.7.1, the upgrading technology suppliers are represented in all sizes of companies. Many small companies may not be listed, because they do not appear in reports.

7.7.1 Technologies

Many of the companies have more than one upgrading technology in their product portfolio, and some also provide anaerobic digestion equipment. Many advertise turnkey solutions on their web pages and provide service solutions. The number of suppliers of upgrading technologies is presented in Figure 7.10.

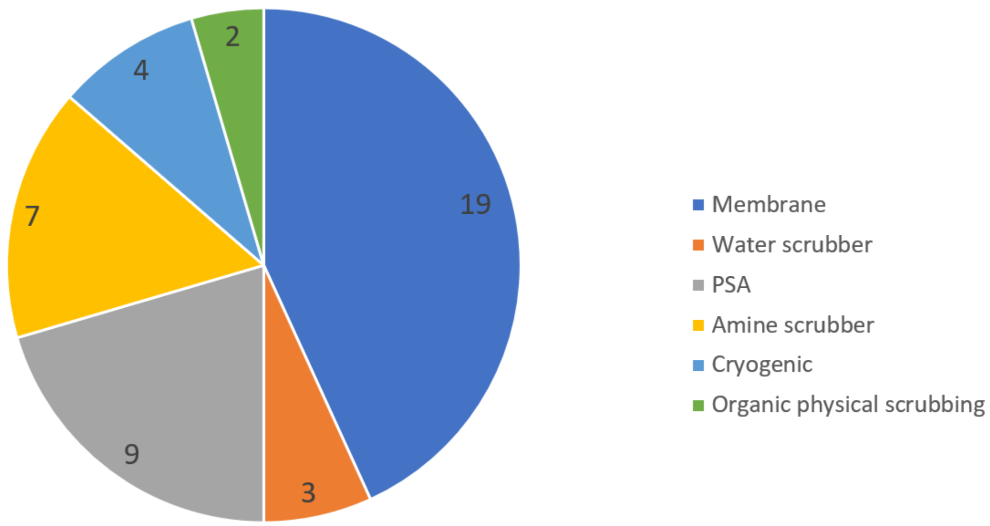

Figure 7.10. *Manufacturers of upgrading technologies. (Bauer, Persson et al. 2013)*

Membrane technology has the most suppliers, with small, medium and large enterprises providing the technology. Most of the companies do not manufacture their membranes but purchase them from other companies such as Evonik. All companies promise a good quality biomethane and low methane slip.

PSA upgrading technology is one of the most widely used upgrading technologies, but it seems that many large companies do not provide it for biogas upgrading. Most of the suppliers are small or medium-sized corporations. The only large corporation that provides the technology is Strabag, which also provides membrane and amine scrubbing technologies. It seems that large corporations are not interested in the technology because it is most suitable for small biogas upgrading plants.

Large companies, such as Wärtsilä, have bought smaller companies that offered **amine scrubbing** technology. Only a couple of small companies are still in business, but there may be more that were just not found during the time of this research. It was apparent that large companies have invested more heavily in amine technology in the last couple of years.

Water scrubbers is the most commonly used upgrading technology, according to Angelidaki et al. (2018). Even so, there are not many suppliers. Water scrubber suppliers are mainly small or medium-sized corporations. It appeared that some companies which previously provided water scrubbers have exited the business.

7.8 Discussion

This chapter discusses the results of the research and how they compare to the literature. This chapter is divided according to the research questions.

The interviews, performed by phone, Zoom or Microsoft Teams, were successful and provided valuable information for this thesis. If the interviews had been done face-to-face at the interviewees' plants, more information could have been obtained. Still, since the interviewees were in different European locations, most interviews would have been done remotely in any case.

Performing the data analysis was difficult because it was hard to determine the reasons for the unscheduled shutdowns just from the available data. Due to the COVID-19 pandemic, a visit to get a physical view of the plants being examined was not allowed.

The most suitable upgrading technology for Valmet?

The interviews support the literature, even though they appeared to contradict each other on the topic of the amine scrubbing properties. Both the interviews and the literature supported the argument that amine scrubbing has the highest quality of methane and lowest CH_4 slip. Membrane separation technology was decisively the second-best upgrading technology for Valmet.

Amine scrubbing technology does not have many suppliers. It seems that large companies believe in this technology. As amine scrubbers operate in atmospheric pressure, the technology can be used easily in other applications.

How to add value to the customer through automation?

Value creation with automation in biogas upgrading was not addressed in the literature. The reason for this may be that the sector is quite new, and the subject is not interesting enough for the academic sector. Despite the lack of literature, the interviewees gave good perspectives on solutions that would create value for the customer. The interviews indicated problems that could be prevented with automation solutions and what system features the interviewees would find most beneficial. Most of the features that interviewees expect can be fulfilled with Valmet DNA. Some of the features that interviewees wished for are not currently implemented in Valmet DNA but could be in the future. Features that are not part of Valmet DNA today include real-time tracking of the upgrading process on a company's web page and the automatic emailing of reports to a recipient.

Black-box automation solutions were one of the main topics that appeared in the interviews and data analysis. Literature on black-box automation was hard to find, but interviewees and employees at Valmet were aware of the problems that a black box can cause. Black-box automation solutions may be especially prominent in the biogas sector because the sector is still relatively new. Some suppliers do not have a lot of experience, and customers do not know to ask for an automation system that is as open as possible. As discussed earlier in Chapter 7.5.1, safety automation has to be protected with passwords to prevent risks. Even though the safety automation needs to be a black box, the automation provider has to offer support to change parameters in the safety automation, if needed. The problems that a black box can cause were highlighted in the data analysis.

Considerable contradiction came up during the interviews about measuring instruments. The value created from measuring instruments could provide a good payback, but not many interviewees are willing to pay a higher price. The added value is essential to bring up in marketing material. Concrete examples could demonstrate to customers how the higher cost in fact advances the operations of their plant.

Companies in the sector may not know to request functional trends and reports. This may change in the future when companies realize what they need and what is useful. An inexpensive automation system may result in poorly implemented reports and trends.

Technologies used by other companies

Water scrubbing technology was interesting because it is the most commonly used upgrading technology, even though there are only a few companies that provide this technology in their product portfolio. Although the technology is established, it seems that large companies are not interested in investing in it. Water scrubbing technology may interest customers, because it is established technology with many references showing it works as promised. Membrane separation technology was found in the product portfolio of many companies, and it appeared from the interviews that many small plants are interested in the technology.

Future development

In one of the interviewee's plants, the control of water scrubbers depended on the CO_2 content in the biomethane. The interviewee said the plant's CO_2 sensor is inaccurate and hoped automation could predict the CO_2 content. Automation can give a prediction if the exact operation principle of the processes is known. Prediction would be an interesting topic to investigate with the interviewee, and solving the problem could help the interviewee's plant operate better. These highly optimized automation solutions are not commonly performed in the biogas sector, because they increase the capital cost of the automation system. Regardless of a high capital cost, the value created can be even more if highly optimized automation helps increase the biogas processing operations and prevent unnecessary shutdowns.

As discussed earlier, the precise adjustment and control of the PSA process with automation is essential to achieve the required biomethane quality and a low CH_4 slip. Process dynamics and how the controllers work in the process is an interesting topic to examine further. The right parameters in the process are essential, so the response of the controllers is vital.

Controller tuning would be another interesting topic to examine. When the process dynamics are accurately known, the controllers can be tuned so that the process operates as closely as possible to the process's physical limit. Controllers may not be tuned as well as they could be, because the automation system in biogas processes is often cheaply implemented to reduce the costs. In small biogas upgrading plants, the cost of proper controller tuning may be too expensive, but in bigger plants (<1000 Nm^3/h) the proper operation of the process would decrease CH_4 slip and thereby increase the energy output of the plants. Optimized controller operation would also increase energy efficiency when the process operates at its highest possible rate. More information about optimized operation of the processes is discussed in Chapter 5.

Combining the biogas upgrading and methanation processes would also be an interesting subject to examine. The CO_2 from biogas upgrading could be used in the methanation process as raw material. The electricity required for the methanation process could be produced locally from wind or solar power. One interviewee has examined the possibilities of combining the processes using solar panels. At the moment, it is not an economically viable option. In the future, however, biomethane could be used as energy storage or power-to-X. The idea behind power-to-X is to use cheap energy from renewable energy sources. More information about the methanation process is presented in Chapter 2.2.1.

8 CONCLUSION

The following topics were examined in this thesis: value creation with automation in biogas upgrading, biogas upgrading technologies and companies who produce biogas upgrading technologies. This research was executed using literature, interviews and data analysis.

Biomethane is a higher-grade biogas product, which can be used to replace natural gas. Biomethane is produced by removing CO_2 in the biogas upgrading process. The biomethane CH_4 content is around 98%. The main upgrading technologies are water scrubbing, organic physical scrubbing, amine scrubbing, pressure swing adsorption, membrane separation and cryogenic separation. All these technologies have their own characteristics and are best suited for a particular application.

Biogas upgrading technologies were examined to determine which technologies could be most suitable for Valmet. An appropriate technology needs to produce good biomethane quality, low CH_4 losses and the possibility of utilizing separated CO_2. Synergies using the same technology for carbon capture and utilization in other applications were also examined. The most suitable upgrading technologies for Valmet are amine scrubbing and membrane separation. These technologies provide excellent quality of upgraded biomethane and low CH_4 slip, and the CO_2 is usable for other applications without any further treatment. Amine scrubbing was especially interesting, because it operates in atmospheric pressure. Thus, it can be used in the carbon capture of flue gas.

The experimental part of the thesis focused on value creation with the use of automation. The primary purposes were to examine what kinds of automation solutions are needed and how automation can create value for the customer. The implementation of the experimental part was carried out through interviews and data analysis. The interviews included 13 thematic interviews, and all of the interviewees had a connection to biogas upgrading. The data analysis included three biogas upgrading plants that used water scrubbing technology. The most common problems and their causes were examined, and the correlation between alarms was examined.

Interviewees emphasized that automation systems need to be as affordable as possible and that inexperience in the field has led to problems. The low price requirement for automation has caused difficulties. Value creation was discussed many times in the interviews, and it was evident that it is possible to create value with automation.

The main methods of creating value with automation are to provide reports, trends, measuring instruments and software, while avoiding black-box automation. Value creation means a decrease in unnecessary shutdowns of the process, easier-to-use failure diagnostics, more reliable processes and easier production tracking for the customer. The main reason for the problems that interviewees pointed out is that their automation systems have often been implemented in the most inexpensive way possible to reduce the capital costs of the automation system.

Reports are critical for biogas upgrading plants operators because they have to report information to public authorities. Reports and trends have been poorly implemented in some plants, and interviewees are hoping these could be made easier and clearer to use. Reports sent automatically to emails was a desired feature. This can be implemented in Valmet DNA. Traceability of the production would help operators to track any low-quality shipments and prevent low-quality gas from entering distribution. Traceability and quality monitoring would also help the biomethane producers to become a more appealing choice for their customers.

Black-box automation cannot be modified or even examined because it is usually protected with a password. Some interviewees have had problems with black-box automation, and the problems have resulted in financial losses. Safety automation has to be protected with passwords, because any unauthorized changes may cause safety risks. The automation supplier and customer need to communicate with each other to prevent unnecessary problems due to black boxes. It is important for the customer to be able to change the configuration in the black box as fast as possible to prevent unnecessary shutdowns.

Reliable and accurate measuring instruments increase reliability and enable optimal process operation. Even though some suitable measuring instruments might increase the capital costs of the automation system, their payback time is short. Accurate measuring instruments would improve the reliability and optimal operation of the process, increasing the quality of biomethane and decreasing CH_4 slip.

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A THEMES OF THE INTERVIEWS

Basic information about the interviewee, company and technology

1. Interviewee's experience in automation and biogas upgrading
2. Upgrading technology, raw material and digestion residue
3. Upgrading technology supplier
4. Reasons for choosing the technology
5. Problems with upgrading technologies

Solutions used by the company in relation to automation and any desired improvements

1. Provider of automation
2. Control of automation
3. Upgrading technology supplier
4. The role of automation in biogas upgrading
5. Integration of different processes
6. Service
7. Problems in automation
8. Dealing with contingencies
9. Alarms
10. Specific points which automation should address
11. Operation of graphic displays
12. Measuring data and instruments
13. Off-gas and carbon dioxide utilization
14. Effect of upgrading automation on plant automation
15. Safety and cybersecurity

16. Important concerns for the end user
17. Future of renewable methane

Automation in value creation

1. Automation in reducing workload
2. Adding more value to automation
3. Further wishes for automation